A STUDY ON STABILIZATION/SOLIDIFICATION OF SOILS CONTAMINATED BY PETROLEUM OIL UTILIZING INDIGENOUS INDUSTRIAL WASTE PRODUCTS

BY
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To my parents,

brothers

and all of my friends

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As once said, “Gratitude makes sense of our past, brings peace for today, and creates a vision for tomorrow”, I would like to take this opportunity to express my thanks and gratitude to my MS Thesis advisor, Prof. Omar S. Baghabra Al-Amoudi, a man from whom I have learned the basics and ethics of doing scientific research. A man who did not hesitate, even for a second, to accept me as a student to work under his supervision and has always been there to guide me.

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LIST OF ABBREVIATIONS

C: Cohesion, kPa

C_c: Coefficient of gradation

$C_{u:}$ Uniformity coefficient

D_{10}: Diameter of particles representing 10% finer material in particle-size curve, mm

D_{30}: Diameter of particles representing 30% finer material in particle-size curve, mm

D_{60}: Diameter of particles representing 60% finer material in particle-size curve, mm

EDS: Energy dispersive spectroscopy

G_s: Specific gravity

LL: Liquid limit, %

MDD: Maximum dry density, kN/m^3

OMC: Optimum moisture content, %

PAH: Polycyclic aromatic hydrocarbons, ppm

PI: Plasticity index, %

PL: Plastic limit, %

S/S: Stabilization/Solidification

SEM: Scanning electron microscope

TCLP: Toxicity characteristic leaching procedure

TPH: Total petroleum hydrocarbons, ppm

UCS: Unconfined compressive strength, kPa

XRD: X-Ray diffraction

ABSTRACT

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Thesis Title: A Study on Stabilization/Solidification of Soils Contaminated by Petroleum Oil Utilizing Indigenous Industrial Waste Products

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Contamination of soils by crude oil and other petroleum products, such as gasoline, kerosene, diesel, etc., commonly takes place due to the leakage and accidental failure of pipes and tankers used for transportation and storage of oil. The leaking oil modifies the geotechnical properties of soil - mostly negative effects - and eventually poses serious threat to the environment and ecological balance. Stabilization/solidification (S/S) technique is an approach that has been used to treat contaminated soils using different types of stabilizers.

In this research, two indigenous soils were contaminated by diesel and crude oil (at 2.5, 5 and 10% by dry weight of the soil) and tested to assess their geotechnical and environmental properties including Atterberg limits, specific gravity, size gradation, maximum dry density, optimum moisture content, and unconfined compressive strength (UCS). An attempt was made to explore the possibility of S/S treatment of these two soils. The stabilizers used were ordinary Portland cement (OPC), cement kiln dust (CKD) and limestone powder (LSP). The contaminated-stabilized soils were evaluated by measuring the changes in compaction characteristics, UCS, permeability, and the heavy metals and hydrocarbons contents.

Results of this investigation indicate that the S/S treatment of contaminated soils improved the compaction characteristics and the UCS. Some S/S-treated mixtures were found to pass the strength criterion of the U.S. Environmental Protection Agency (USEPA) using the UCS test results. The mixtures that passed the UCS requirements were tested to measure their heavy metals content through the toxicity characteristic leaching procedure (TCLP), total petroleum hydrocarbons (TPH) and polycyclic aromatic hydrocarbons (PAH). Only few S/S-treated mixtures were found to pass the strength criterion to be used as a sub-base material, based on the American Concrete Institute

(ACI) criterion using the UCS test results after 7 days of air curing. These successful mixtures were tested to assess California bearing ratio (CBR) to explore the possibility of using these mixtures as sub-base materials.

Finally, scanning electron microscope (SEM) and X-ray diffraction (XRD) analyses were used to study the changes in the micro-structure of the stabilized soils. In the case of contaminated sand (for both diesel and crude oil), the best performance by the stabilizers was achieved by mixing the soil with 10, 20 and 40% LSP by the dry weight of the soil (with the addition of 2.5% OPC for the three cases). For the contaminated marl, in the case of diesel contamination, the best performance was achieved by the addition of LSP (10, 20 and 40%) and CKD (5, 10 and 20%) while for the crude oil, the addition of LSP (10, 20 and 40%) has achieved the best results.

ملخص الرسالة

الاسم الكامل: ياسر مبارك حسين مصطفى

عنوان الرسالة: دراسة حول معالجة وتصليب التربة الملوثة بالنفط باستخدام مخلفات المنتجات الصناعية

التخصص: هندسة مدنية

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يحدث تلوث التربة بالمنتجات النفطيه مثل الجازولين، الكيروسين والديزل... إلخ، نتيجة الحوادث والتسريب من ناقلات النفط والأنابيب والخزانات. ويؤدي النفط المتسرّب إلى حدوث تغييرات سيئة في التربة، مما يهدد التوازن البيئي والحيوي. وتعتبر طريقة التصليب/المعالجه (S/S) إحدى الطرق المستخدمة لعلاج التربة الملوثة باستخدام انواع مختلفة من المواد المعالجة. تهدف هذه الدراسة للتحقق من إمكانية معالجة نوعين من التربة المحلية والملوثة بجرعات مختلفة من الديزل والنفط الخام. وتم دراسة تأثير الديزل والنفط الخام (المضافين بنسبة 10% & 2.5,5 من الوزن الجاف للتربة) على خواص التربة، حيث أن نتائج هذه الدراسه أثبتت أن إضافة الملوثات للتربة قد أثر بوضوح على خواصها الأساسية، مثل مستوى الليونة (Atterberg Limits)، الكثافة النوعية، الكثافة الجافة، نسبة الماء المثلى وقوة مقاومة القص (UCS).

تم معالجة التربة باستخدام ثلاث أنواع من المواد المعالجة (المثبتات) ، وهي: الاسمنت البورتلاندي العادي (OPC)، غبار أفران الإسمنت (CKD) ومسحوق الحجر الجيري (LSP)، ومن ثم تم اعادة اختبار خواص الدمك وقوة القص والنفاذية بالإضافة لمحتوى الهيدروكربونات والمعادن الثقيلة. وقد ساهمت إضافة المواد المعالجة في تحسين خواص الدمك والقوة. وتم اختبار بعض العينات التي حققت شروط القوة للتحقق من نسبة النفاذية بالإضافة إلى إختبارات TCLP, TPH, PAH. أثبتت النتائج المتحصل عليها نجاح المعالجة بالنسبة لمعايير USEPA. وتم اختبار العينات بعد المعالجة للتحقق من إمكانية استخدام التربة المعالجة كطبقة ساندة في الطرقات حسب متطلبات ACI والتي تعتمد على مقدار القوة المتحصل عليها خلال 7 أيام من المعالجة. وتم إجراء إختبار CBR على العينات التي حققت شروط ACI. وأظهرت النتائج إمكانية استخدام التربة المعالجة كطبقات ساندة في الطرقات. وأخيرا، تم إجراء اختبارات SEM & XRD لدراسة التغير في البنية الداخلية للتربة. أظهرت النتائج في حالة الرمل الملوث بالديزل والنفط الخام أن إضافة LSP بنسبة 40% & 20 ,10 من الوزن الجاف للتربة الملوثة بالإضافة إلى 2.5% OPC قد حققت أفضل النتائج. وفي حالة المارل الملوث، فإن أفضل النتائج كانت عندما تمّ إضافة LSP (40% & 20 ,10) و CKD (20% & 10 ,5) في حالة التلوث بالديزل، أما في حالة التلوث بالنفط الخام، فإن إضافة LSP بنسبة 40% & 20 ,10 قد أعطت النتائج المرجوة.

CHAPTER 1

INTRODUCTION

1.1 Soil Contamination

Soils are formed due to the interaction and decomposition of different materials including organic and inorganic materials within many years (thousands or may be millions!!). These materials react with each other under some specific conditions (pressure, temperature, etc.) to form the soil. Thus, with the huge variation between those materials, the soil properties vary from place to place. Hence, different types of soils are formed. This variation in the soil properties results in different chemicals composition, different crystalline structures and thus different behavior (Mitchell and Soga, 2005).

The soil is said to be contaminated when it reacts or mixed with some outer chemicals in a manner that its properties are affected and changed. This change could have positive or negative impacts, but mostly the word ‘’contaminated’’ refers to the negative effects. An example of the positive effect is the chemical stabilization of soil, where the soil can be treated with different materials (cement, lime … etc.) to improve its strength or other engineering properties. Soil contamination depends on many factors that include -but not limit to- the following:

- The past and current use of land, whether it is an agricultural land or it has been used for industrial purposes such as mining and petrochemicals production;
- The location of the polluting sources; and
- The depth of water table within the contaminated soil.

It should be noted that soil contamination does not affect the soil geotechnical properties only. It may have its adverse effects on both human's health and other ecosystems. Scientists from toxicology, ecotoxicology and radioecology fields are studying the effect of the contaminants and how to mitigate their impacts (Perk, 2006).

1.2 Sources of Contaminants

There are primarily three main sources of soil contaminants which are mentioned below. The quantity of contaminants produced from a specific source is different from the other sources. Some contaminants can be produced intentionally from human activities like wastes from industries; while others are produced naturally such as ammonia from plants. These sources are (Perk, 2006):

1) Dumping of solids and liquid wastes into large ponds, rivers or any place is the main and most visible source of pollution. The wastes that are produced from the industries and mines are sources of various types of pollutants including: Ammonia (NH_3), methane (CH_4) and hydrogen sulphide (H_2S). Also, it should be noted that the industrial wastes are very fine materials and can affect the soil properties the most. All these problems have forced the governments around the world to restrict wastes dumping.

2) The application of fertilizers and pesticides in the agricultural lands to improve the vegetable production and protect them from insects. Both the fertilizers and pesticides may contain heavy metals such as copper (Cu) and mercury (Hg). The effects of fertilizers which are injected in the soil to enhance its performance may be less than that of the pesticides which are sprayed on the plants. The fertilizers supply the soil with the required nutrients to improve the production, but if the soil receives several nutrients larger than the required, adverse effects may be observed.
3) The atmospheric dusts or the deposition of such chemicals originated from power and chemical plants and the traffic. Examples of these pollutants include the sulphur dioxide (SO_2), nitrogen oxide (NO_x) and ammonia. With the presence of oxygen and other chemicals, these compounds will be converted by other atmospheric reactions into acids like sulphuric and nitric acids (H_2SO_4 and HNO_3).

1.3 Methods of Treatment

There are many different methods of treatment for contaminated soils. These methods differ from each other by their methodology, duration, effects and cost. Logically, the easiest method of treatment is to remove and replace the contaminated portion of the soil by another good quality soil that is suitable in the case that the contaminated soil cannot be treated. Unfortunately, this solution is most often not acceptable because the volume of polluted soil can be large and it will be costly to remove it. Hence, some treatment methods have to be discussed in this research in order to arrive at the best possible treatment to be used in the case of indigenous soils. Based on the treatment mechanism, the most commonly used methods of treatment are the following (Meuser, 2013):

- Physical or chemical methods;

- Thermal treatment methods; and
- Biological treatment methods.

Under each category, a number of methods are used as detailed in the following section:

1.3.1 Physical Methods:

1) **Soil Vapor Extraction:** This method depends on extracting the contaminants from the soil by applying vacuum suction through the soil media, as shown in Figure 1.1. One of the main disadvantages of this method is that it may take between one to three years to totally clean the soil. After that time, the soil may, sometimes, need applying another method to completely remove the pollutants. Only volatile and semi-volatile organic contaminants can be removed with this method (USEPA, 2006).
2) **Solidification/Stabilization (S/S):** This is a new technique whereby the contaminated soil is converted into a solid body (solidification) that has lost its toxic properties. This method produces a stabilized mixture with high resistance to leaching. Additives are often used in this treatment process, like fly ash, lime and Portland cement (as in the stabilization of normal soil). By stabilizing the soil, the pollutants are trapped in the soil, thereby preventing them from escaping the soil structure (Koyuncu et al, 1998). The stabilization and mixing can be carried out by the usual methods used for soil mixing and stabilization, like vertical auger mixing and injection grouting. This method is more economical and faster than the other methods. The treated soil can be reused as a road material, etc.
3) **Soil Flushing:** In this method, the polluted area is flooded with water or any other solution to remove the contaminants from the soil by the solubilization. After the

fluid passes the polluted area, it can be pumped out and recycled again (USEPA, 2006).

4) **Electro-Kinetic Separation:** This is the best method for heavy metal extraction. It depends on applying direct low current through the soil. Electrode pairs are inserted into the contaminated soil mass at the sides (the soil mass is between the two electrodes). Hence, during the process, the negatively charged species, like chloride and nitrate, move towards the anode while the positively charged ones move towards the cathode, as shown in Figure 1.2 (USEPA, 2006). Some soil characteristics may negatively affect the efficiency of this method, such as high organic content, high cation exchange capacity and low moisture content. This method can be enhanced by injecting some chemicals into the soil like nitric acid and acetic acid (Chung and Kang, 1999).

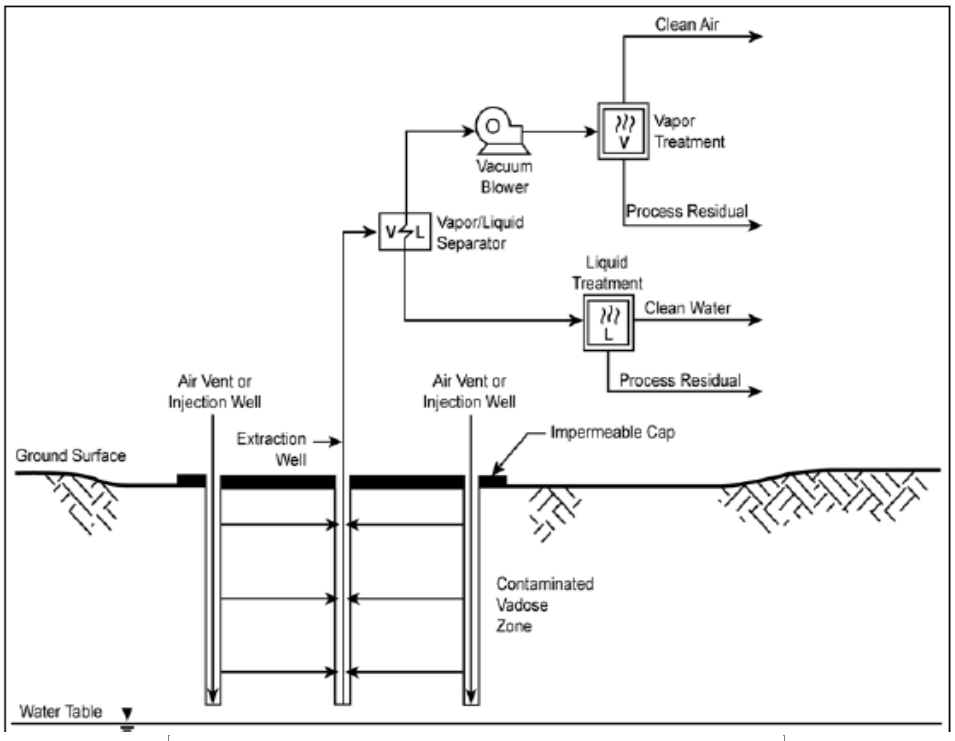


Figure 1.1: Soil Vapor Extraction (USEPA, 2006)

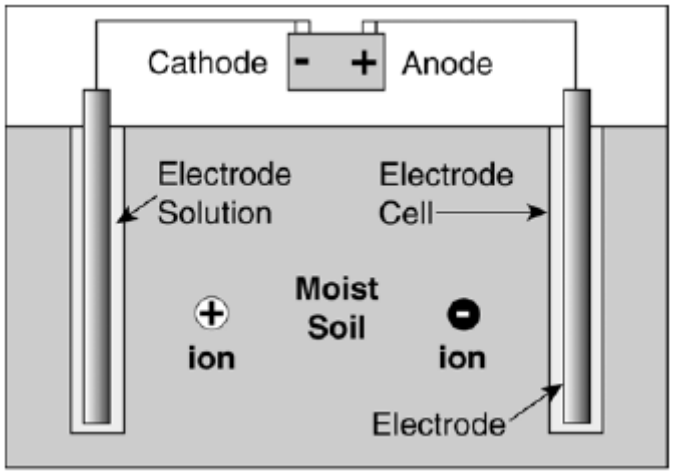


Figure 1.2: Electro-Kinetic Separation (USEPA, 2006

1.3.2 Thermal Treatment Methods:

These types of methods depend on raising the temperature of the soil by applying heat to the system which will enhance and increase the efficiency of contaminants removal. Hence, these methods are complementary to other methods. They can be used along with other methods to speed up the treatment process. There are mainly three thermal applications:

1) **Electrical Resistance Heating:** This is like the Electro Kinetic method, whereby an array of electrodes is placed in the contaminated soil. The movement of the current through the soil and the resistance of the soil will produce the heat. The generated heat will help in accelerating the rate of solvent removal and thus saving time and money (Farrar et al, 2010).
2) **Steam Injection and Extraction:** In this method, a steam with a specific temperature is injected into the ground through some wells that penetrate the soil. With time, the viscosity of the oil will be reduced and thus it will be easily pumped out of the soil.

Unfortunately, this method has two main disadvantages, the first being its dependence on the permeability of the soil. At low permeability, the steam will not be able to penetrate the soil easily, which will produce low efficient results. The other disadvantage is that it depends on the type of soil; soils with high organic contents can bind some organic compounds and thus preventing their full removal from the soil (Davis, 1998).

3) **In-situ Vitrification:** This is the most effective method that depends on producing high temperature (1200 to 2000 ^{o}C), which can melt the contaminants, and it is most efficient against soil with high amount of organic matters. The principle of this method is like that of Electrical Resistance Heating, where high voltage is applied to the soil through electrodes to produce the high heat (USEPA, 1995).

1.3.3 Biological Treatment Methods:

Unfortunately, these methods require a lot of time. Hence, they are not applicable in the geotechnical field. Examples of such methods are mentioned below (USEPA, 2006):

1) **Phytoremediation:** In this process, plants are used to stabilize or remove soil contaminants. Over the past 20 years, this technology has become popular and has been employed at sites with soils contaminated with lead, uranium, and arsenic. Unfortunately, this method is applicable for shallow depth contamination (e.g. the depth of the plants' roots).
2) **Biosparging:** It is a treatment technique using natural microorganisms, like fungi, to decompose hazardous soil substances.

1.4 Why Choosing the S/S Technique

As indicated by Wilk (2004), stabilization/solidification (S/S) is a term that involves different categories. The word “stabilization” refers to the process in which chemicals are added to the contaminated medium to change its chemical composition, resulting in less toxic material. However, the word “solidification” refers to the physical changes in the contaminated medium by increasing its density and thus its compressive strength (Wilk, 2004).

The S/S technology used to treat contaminated soils involves mixing of the contaminated soil with one of the additives, termed as ‘stabilizer’, such as Portland cement, lime, fly ash, etc., that results into immobilization of the contaminants within the soil thereby stopping leaching of the contaminants and protecting the groundwater from pollution (Paria and Yuet, 2006). The improvement in the properties of S/S-treated soils is achieved due to cation exchange, agglomeration and cementing. The improvement in the soil properties, in terms of its unconfined compressive strength (UCS), cohesion and angle of internal friction, etc., can be attributed to new formations, such as calcium silicate hydrates (C-S-H) that coat and bind the soil particles (Shah et al, 2002).

The in-situ application of S/S technology for treating contaminated soils involves the following steps (Wiles, 1987):

a) Excavation of the contaminated soil;
b) Screening and crushing of over-sized pieces;
c) Characterization of soil samples;
d) Buffering of the soil pH;

e) Mixing of the contaminated soil with the selected stabilizer;

f) Testing the treated soil to evaluate the effectiveness of the treatment; and

g) Utilizing the treated soil as a construction material such as sub-base material for road construction.

The S/S technology has been used in USA for more than 30 years and is termed as one of the top five treatment technologies by the Environmental Protection Agency (EPA) (USEPA, 2000). In UK, the contaminated soils were removed and kept in landfills, but it was found that landfill technique does not solve the problem but transfers it to another place and time. Therefore, S/S technology has recently been used a lot to avoid the accumulation of contaminated soils (Jones et al, 2001). Since that time, regulations and targeted values have been described in the different standards for the treated soils.

1.5 Project Objective:

The main objective of the research was to explore the possibility of using indigenous industrial waste materials such as cement kiln dust (CKD) and limestone powder (LSP) for the stabilization and solidification of some local soils contaminated by petroleum products. To achieve this objective, an experimental program (Figure 1.3) was conducted to assess the variation in the geotechnical and leachability properties of the treated and untreated soils.

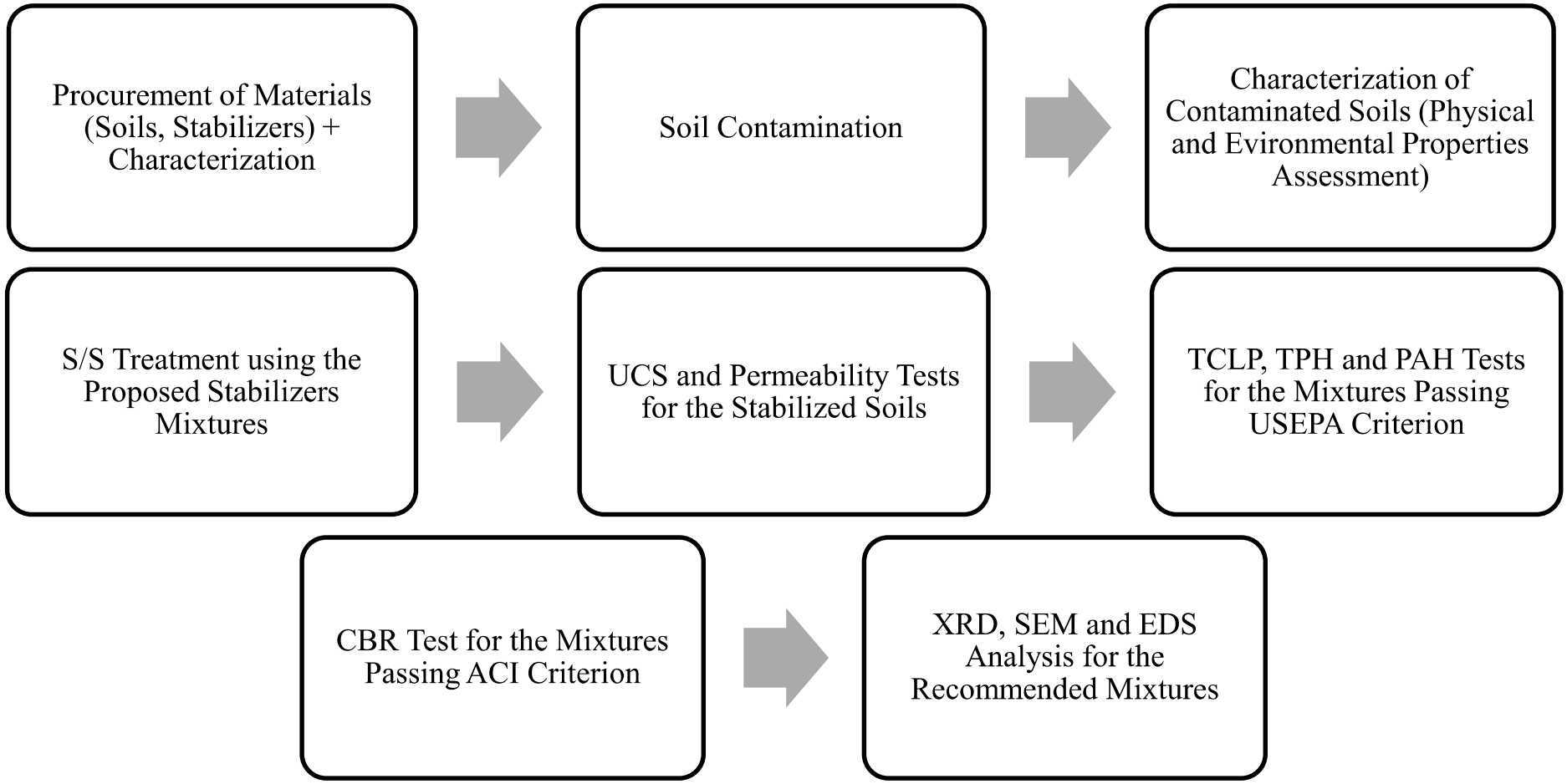


Figure 1.3: Summary of the Experimental Program

CHAPTER 2

LITERATURE REVIEW

Soil contamination by oil is one of the most common type of contamination that results in changing the soil behavior and its geotechnical properties (Rehman et al, 2007). Oil can reach the soil from different sources, like oil spills from tanks, leakage from pipes and underground storage tanks, failure of equipment, etc. (ITOPF, 2015). According to the International Tanker Owners Pollution Federation (ITOPF), large amounts of oil spills were recorded since 1970s until recent years. Although the number of accidents is decreased significantly, oil leakage from other sources is still expected (ITOPF, 2015).

2.1 Oil Spill Accidents

According to ITOPF, between 2010 and 2014, a total number of 35 oil spill accidents was recorded. Nine of these accidents were large spills (greater than 700 tones!!). Considering this huge amount of oil, precautions should be taken to prevent such accidents in the future and to minimize the effects of oil on the environment and soil geotechnical properties. It should be noted that these numbers are just indicating the spills that from tanker and that some other small accidents are not recorded (ITOPF, 2015). The major oil spill accidents that happened since 1970s are shown graphically and numerically in both Figure 2.1 and Table 2.1, respectively.

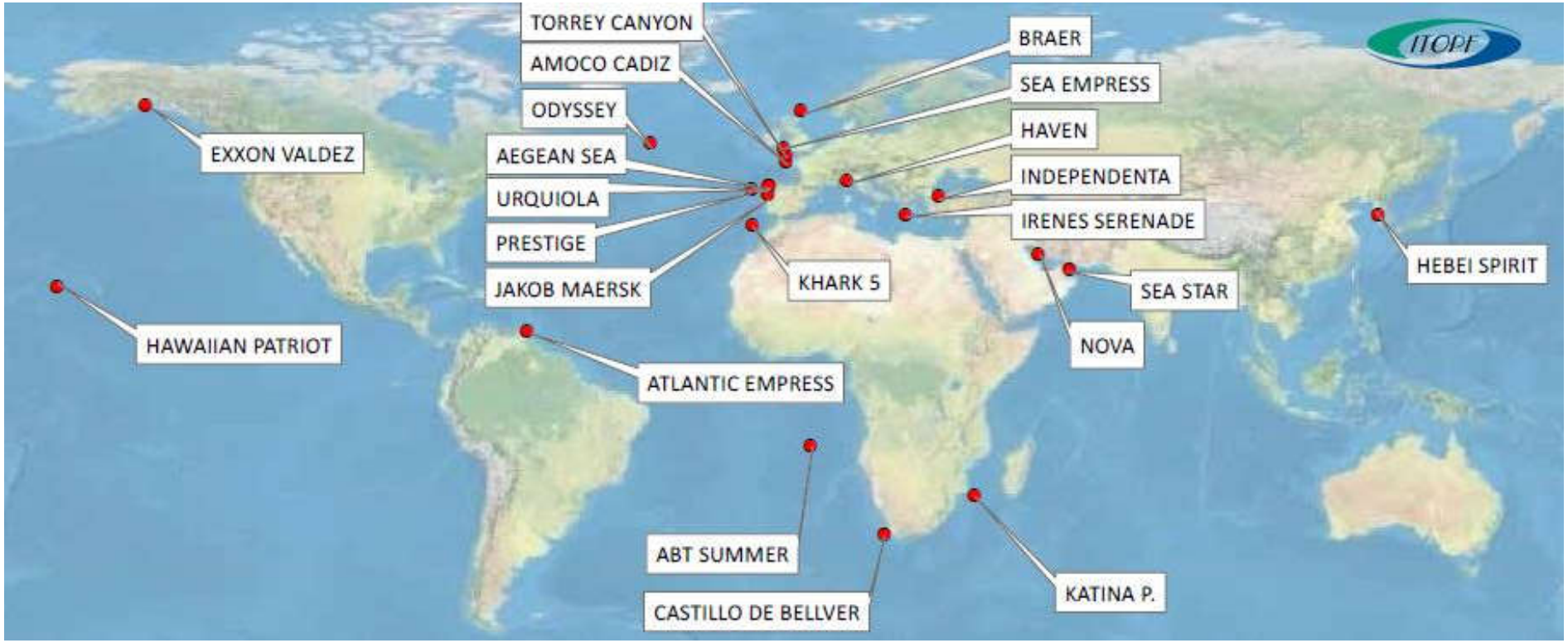


Figure 2.1: Major Oil Accidents (ITOPF, 2015)

Table 2.1: Major Oil Spill Accidents (ITOPF, 2015)

Location	Year	Spill size (tones)
Off Tobago, west India	1979	287,000
700 miles from Angola coasts	1991	260,000
Off Saldanha Bay, South Africa	1983	252,000
Off Brittany, France	1978	223,000
Genoa, Italy	1991	144,000
700 miles from Nova Scotia coast, Canada	1988	132,000
Scilly Isles, UK	1967	119,000
Gulf of Oman	1972	115,000
Navarino Bay, Greece	1980	100,000
La Coruna, Spain	1976	100,000
300 nautical miles off Honolulu	1977	95,000
Bosphorus, Turkey	1979	94,000
Oporto, Portugal	1975	88,000
Shetland Islands, UK	1993	85,000
La Coruna, Spain	1992	74,000
Milford Haven, UK	1996	72,000
120 nautical miles off Atlantic coast of Morocco	1989	70,000
Off Kharg Island, Gulf of Iran	1985	70,000
Off Maputo, Mozambique	1992	67,000
Off Galicia, Spain	2002	63,000

2.2 Effects of Oil Contamination on Geotechnical Properties of Soils

It was found from different studies and researches that soil saturation by any fluid that is characterized by physico-chemical properties like high viscosity, will result in deterioration and disturbing the soil engineering properties (Amadi et al, 2012). The degree and extent of the contamination depend on different factors. Mainly, the chemical composition of the contaminants, whether it is oil or heavy metals, and the physical and chemical composition of the soil. Knowing these factors, one can define the best treatment methods or to use the contaminated soil in different applications (Khamehchiyan et al, 2007).

Evgin and Das (1992) performed triaxial tests on quartz sands (both clean and contaminated) using both loose and dense samples. They found that contamination by motor oil will result in significant reduction of friction angle and increase in the volumetric strain (deformation).

In 1995, the effects of oil on the properties of Kuwait sand was reported (Al-Sanad et al, 1995). The researchers polluted different samples artificially with about 6% or less of the dry weight of the soil to match the actual conditions in the field. Their results indicated small reduction in permeability and strength and an increase in the compressibility due to the contamination.

Aiban (1998) performed a laboratory investigation to study the effect of temperature variation on strength, permeability and compressive strength of a local sand that was contaminated by two types of crude oil (heavy and medium). It was found that with increasing the contamination level, the maximum dry density and angle of internal

friction would decrease with increasing the contamination level (4.7% and 5.3%, respectively). He found that with the increase in temperature above room temperature for the contaminated soil, higher compressibility and deformation were recorded while the strength parameters, such as the angle of internal friction and cohesion, were not sensitive to the temperature variation.

In 2001, Shin and Das studied the effect of contamination by three different types of oil (engine, lamp and crude oil) on the bearing capacity of unsaturated sand. The oil content varied between zero and 6% of dry soil weight. It was found that for unsaturated oil-contaminated sand, the bearing capacity was reduced with increasing the oil content. Since the bearing capacity is highly dependent on the angle of internal friction (Bowels, 1997), a series of direct shear tests were carried out on the contaminated soil. A reduction of nearly 23% in the angle of internal friction was recorded.

According to Shah and his colleagues (2002), they reported that the oil contamination of soil decreases the maximum dry density by 4%, cohesion by 66%, angle of internal friction by 23% and unconfined compressive strength by 35%. Further, they reported an increase in the liquid limit by 11%.

A study was conducted by Khamehchiyan and his colleagues (2007) to investigate the effect of crude oil on the geotechnical properties of clay and sand. They used higher oil content than the other researchers (from zero to 16% by dry weight of soil). They found out that oil contamination resulted in decrease of both permeability and shear strength parameters for both sand and clay. Since oil is volatile and can evaporate at room

temperature, they modified the usual equation used to calculate the water content into the following one:

$$\omega\% = (1 + mn)\frac{W_t}{W_d} - (1 - n)$$

Where:

W_t: wet weight of contaminated soil;

W_d: dry weight of contaminated soil;

m: oil content after drying; and

n: oil content before drying.

The effect of clayey soil contamination by kerosene up to 7.5% of the dry weight of the soil indicated that the addition of the kerosene increased both the liquid limit and the optimum moisture content of the soil and reduced the maximum dry density (Vipulanadan and Elesvwarapu, 2008). Nazir (2011) conducted some tests to investigate the effects of motor oil on over-consolidated clay. He placed some clay samples in oil tank and pressurize them under 65 kPa (equivalent to the overburden pressure that acted on them in-situ). He considered the effects on Atterberge limits, permeability and unconfined compressive strength. In addition, he considered the effect on the compressibility characteristics and found out the following:

- The Atterberge limits were reduced along with the permeability.
- The unconfined strength was reduced by large value (35%).

To be mentioned, the clay that was used for this experiment contained 72% montomorolinite, 18.2% kaolinite and 9.8% illite.

Amadi and Eberemu in 2012 studied the effects of three different organic chemicals on the soil geotechnical properties; those are the benzene, ethanol and kerosene. The soil was contaminated with different dosages (2.5, 5, 7.5 and 10% by soil dry weight). It was found that the plasticity, unconfined compressive strength and maximum dry weight were reduced with contamination while the hydraulic conductivity increased (Amadi et al, 2012). Further, a recent study was conducted by Abbawi and her colleagues in 2013 to assess the bearing capacity of soil contaminated with kerosene. Their results indicated an increase in the bearing capacity with kerosene weight up to 5% of the dry weight of soil, however, increasing the kerosene percentage beyond 5% decreased the bearing capacity (Abbawi et al, 2013).

Alhassan and Fagge in 2013, published the results of the effect of different types of petroleum products (crude oil, vacuum gas oil and low point pour fuel) on the geotechnical properties of three types of soil (sand, clay and lateritic soils). All the three types of soil exhibited similar behavior for both CBR and shear strength as CBR decreased and shear strength increased with increasing the contamination level for the three types of soil. However, it should be noted that there were variation and different response to the type of contaminant although the sand and lateritic soil exhibited similar behavior (Alhassan and Fagge, 2013).

The effects of kerosene and gasoline on the geotechnical properties of coarse grained soil were assessed by Rasheed and his colleagues (Rasheed et al, 2014). The soil was contaminated by up to 7.5% by dry weight and it was found that both the maximum dry density and optimum moisture content decreased along with cohesion and CBR values. On the other hand, both the liquid and plastic limits along with the angle of internal

friction had increased with increasing the contamination ratio. An important note is that gasoline effects were greater than those of kerosene. Furthermore, it is important to study the effects of different petroleum products since they may have different effects from each other.

The effect of crude oil on the compaction characteristics of residual (lateritic) soil was assessed in a study by Oluremi et al. (2015). Crude oil was simulated by combining different petroleum products at different dosages (kerosene, engine oil, gasoline and diesel). By contaminating the soil with different dosages of crude oil from 0% up to 8%, it was found through gradation curves that the gravelly-formed particles were increasing and the fine portion was decreasing. This is because oil leads to agglomeration and then increasing the volume of large particles, as discussed in a previous study (Rehman et al, 2007). Other properties that were assessed included the optimum moisture content, maximum dry density and unconfined compressive strength (UCS). A visible decrease in the maximum dry density was observed while the optimum moisture content increased with increasing the contamination degree. UCS value tended to increase up to 2% then it started to decrease until it was lower than the original UCS value of the soil (decreased by 80%).

From the previous discussion, it could be concluded that oil contamination affects the geotechnical properties in general and there are some variations in these effects between different soil types depending, as mentioned earlier, on both the chemical composition of the oil and its dosage. Table 2.2 displays some of the results that were discusse

Table 2.2: Summary of Some of Previous Studies

Author	Soil type	Contaminant	Contamination percentage	G_s	MDD	OMC	LL	UCS	K	C	ϕ	CBR
Oluremi et al. (2015)	Lateritic Soil	Crude Oil	0, 2, 4, 6 and 8%	-	↓	↑	↓	↓	-	-	-	-
Vipulanandan, and Elesvwarapu (2008)	Clayey Soil	Kerosene	0, 2.5, 5 and 7.5%	-	↓	↑	↑	-	-	-	-	-
Rasheed et al. (2014)	SP-SM	Kerosene Gasoline	0, 3, 5 and 7.5%	↓	↓	↓	↑	-	-	↓	↑	↓
Alhassan and Fagge (2013)	Sand, Clay and Laterite Soil	Crude Oil Vacuum Gas Oil Low Point Pour Fuel Oil	0, 2, 4 and 6%	-	-	-	↓	-	-	↑	↑	↓
Rehman et al. (2007)	Clay	Crude Oil	Full Saturation	-	↑	↓	↑	-	-	↓	↑	-
Rahman et al. (2010)	Basaltic Residual Soil	Engine Oil	0, 4, 8, 12 and 16%	-	↓	↓	↓	-	↓	↓	↑	-
Nazir (2011)	Clay	Motor Oil	Full saturation	-	-	-	↓	↓	↓	-	-	-

Table 2.3: Continued

Author	Soil type	Contaminant	Contamination percentage	G_s	MDD	OMC	LL	UCS	K	C	ϕ	CBR
Khamehchiyan et al. (2007)	Sand and Clay	Crude Oil	0, 2, 4, 8 and 12%	-	↓	↓	↓	↓	↓	↓	Decrease for sand and increase for clay	-
Al-Sanad et al. (1995)	Sand	Crude Oil	0, 2, 4 and 6%	-	↑	↓	-	-	↓	No cohesion	↓	↓

2.3 Stabilization/Solidification of Oil-contaminated Soil

Malone et al. (1982) defined the S/S technic as a method at which the contaminants are immobilized and the surface area of soil is reduced to prevent further reaction between the contaminants and soil particles and improve the geotechnical and physical properties of the soil. The name of this method is combining two processes (as mentioned in Chapter 1), which are the stabilization and solidification. The stabilization process will reduce the leach of the contaminants through the soil structure by building a matrix of binding materials (cement, CKD, etc) (Malone et al, 1982, Paria and Yuet, 2006). On the other hand, the solidification refers to the improvement in the physical properties of the soil, which makes it easier to handle. The treated soil can then be transferred to landfill since the leaching will be minimized or it can be used in other engineering applications.

2.3.1 Evaluating the Effectiveness of S/S Treatment

The effectiveness of S/S treatment is evaluated by determining the physical, engineering and chemical properties of the treated soils. The degree of effectiveness of S/S treatment can be determined in terms of strength and the leaching resistance of the treated soil (Malviya and Chaudhary, 2006). However, the micro-structural examination of the S/S-treated soil might provide a better understanding of the effectiveness of S/S treatment process (La Grega et al, 2001). Scanning electron microscope (SEM) and X-ray diffraction (XRD) tests are often used for the micro-structural examination (Means et al, 1994).

The common tests conducted on S/S-treated soils for evaluating the effectiveness of the S/S treatment include the following: unconfined compressive strength (UCS),

permeability, and leachability tests. The UCS test is performed according to ASTM D2166 while the CBR test is conducted on laboratory-prepared samples in accordance with ASTM D1883. The permeability test on S/S-treated soil is usually carried out in accordance with the ASTM D2434. The leachability of S/S-treated soil is determined using the contaminant leaching procedure (TCLP), which is designed to simulate the leaching potential of a contaminant within the soil. TCLP test is conducted on the samples derived from tested specimens used for strength testing to determine the heavy metal leachability according to the procedure given by the US Environmental Protection Agency (USEPA, 1995).

2.3.2 Applications of S/S Treatment on Oil-contaminated Soils

As discussed in Section 2.1, oil products can affect both the geotechnical and the environmental properties of the soil. Therefore, treatment of oil-contaminated soils is a must if it was found in any site. Many studies were carried out to evaluate the effectiveness of the S/S method in dealing with oil-contaminated soils (Yilmaz et al, 2003; Botta et al, 2004; Al-Rawas et al, 2005; Srivastava et al, 2010). Good reviews were presented by several authors to describe the S/S treatment (Malviya and Chaudhary, 2006; Paria and Yuet, 2006).

Bates et al. (2002) presented a study conducted in USA to find how much the soil-cement mix would prevent the heavy metals and organic compounds from leaching. A specific type of bentonite additive was added to the soil and good results were obtained. The addition of bentonite additives was ascribed to the fact that some other researchers found high concentration in leachate solution when mixing the soil with cement only (Sora et al, 2002).

Al-Rawas and his colleagues conducted experiments on oil-contaminated soil (contaminated by crude oil) to see how much the geotechnical and environmental properties are affected. They treated the soil with cement and cement by-pass dust at different dosages. It was found that the addition of stabilizers improved the soil properties by increasing the strength and cohesion and decreasing the permeability. One important note is that the organic compounds of crude oil acted as retarding agents for cement hydration resulting in low strength compared to the uncontaminated soil. After treatment, there were some traces of heavy metals, such as barium and cadmium, through leaching but they did not exceed the EPA limits (Al-Rawas et al, 2005).

Srivastava and his colleagues (2010) conducted a research on a diesel-contaminated soil. The soil was treated with CKD at different dosages (2, 6 and 14% by dry weight of soil). The geotechnical properties were affected by the diesel contamination as both the specific gravity and the plasticity index decreased. The addition of CKD resulted in reduction in the maximum dry density and increase in the optimum moisture content with the increase in CKD dosage. Further, the UCS increased with increasing the CKD dosage until the soil regain its original UCS before contamination (Srivastava et al, 2010). Amadi and Eberemu (2012) used CKD as a stabilizer for lateritic soil that was contaminated with benzene, kerosene and ethanol. After applying the CKD (10% by weight), the soil properties improved visibly. This improvement was ascribed to the pozzolanic effect of CKD and the formation of new cementing compounds.

A local study was performed by Banaimoon (2013) on oil-contaminated soil obtained from Al-Jubial area, eastern Saudi Arabia. The soil was treated with four different types of stabilizers (cement, cement kin dust, limestone powder and electric arc furnace dust).

The study revealed improvement in the geotechnical properties of the soil and it showed that the treated soil satisfied the United States Environmental Protection Agency (USEPA) requirements.

Another study was conducted on sandy soil (George et al, 2014), whereby the soil was artificially contaminated with diesel (12% by dry weight of the soil). Then, it was treated with fly ash at three different dosages (20, 40 and 60% by dry weight of soil). The soil (treated and contaminated) was tested to examine the effects of the diesel and the fly ash on the geotechnical properties (Atterberg limits, compaction characteristics, UCS and CBR). The presence of fly ash increased the liquid limit of the contaminated soil by up to 40% then it started to decrease. For the compaction characteristics, similar results to Srivastava et al. (2010) were observed (reduction in maximum dry density and increase in optimum moisture content) while the CBR value increased with increasing the fly ash content.

From the previous discussion, it can be concluded that using stabilizers like cement, fly ash, etc., will improve the soil properties and make it possible to use the treated soil in other engineering applications instead of dumping it in landfills or any other place (Al-Rawas et al, 2005).

2.4 Soils in Saudi Arabia

Saudi Arabia is located at the Arabian Peninsula, which is considered as a large crustal plate that is composed mainly of volcanic (on the western province) and sedimentary rocks (at eastern and partly central provinces) (Al-Sayri and Zotl, 1978). Figure 2.2 shows graphically the locations of different geological formations at different times all

over Saudi Arabia. The predominant types of soil that are available in eastern Saudi Arabia are mainly four, those are: sand, sabkha, marl and clay. Sabkha soil (or salts flats) is covering the shorelines all the way from Kuwait until the southern end of the Arabian Gulf. It is composed of layers of sand, silts and salts to a depth of several meters (Al-Amoudi, 1999). On the other hand, clay is found on several locations, like the Red sea and the Arabia Gulf shorelines, Al-Jauf and Tauk formations (Sheta et al, 2006).

Unfortunately, both the clay and sabkha are not being used in engineering construction since they are both sensitive to water (Aiban et al, 1998). On the other hand, sand is cohesionless in nature and requires cement stabilization to develop sustainable strength and durability. Many studies were carried out to enhance the geotechnical properties of sand in order to make it applicable for different engineering applications (Al-Homaidy, 2013). Therefore, marl soils became the only candidate to be used in engineering and construction applications, such as base and sub-base layers, filling materials, etc. (Al-Amoudi et al, 2017). In this study, both the sand and marl (that are locally available) were used in order to assess the effects of contaminations on their properties and how to stabilize and solidify them after contamination.

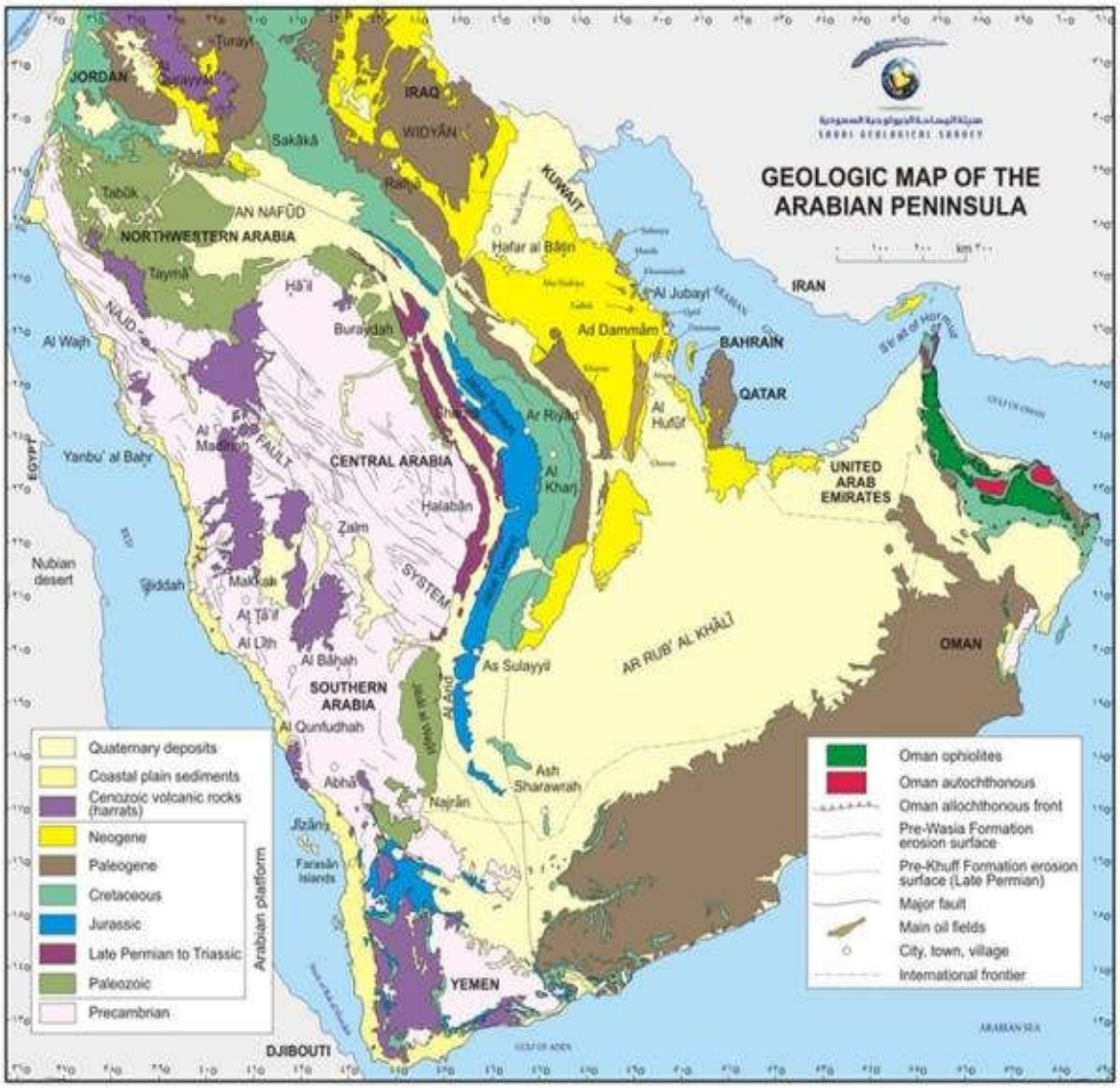


Figure 2.2: Geological Formations in Saudi Arabia at Different Times (Saudi Geological Survey, 2017)

2.4.1 Dune Sand

As was shown in Figure 2.2, sand is covering a large part of Saudi Arabia (almost one third). This sand is called eolian sand (also spelled aeolian sand), which is formed due to the wind movements and capability of eroding the surfaces of rocks. The wind erodes and shape the surface of rocks, then it transports and deposits the soil particles at different locations (Ho et al, 2014). This aeolian sand is made up of quartz (SiO_2), which is the most stable mineral among rock-minerals (Mitchell and Soga, 2005).

The dune sand formations are found in three parts of Saudi Arabia, namely, Al-Rub' Al-Khali, Ad-Dahna and An-Nafud deserts (see Figure 2.2). Most of the sands that are found in these deserts are formed primarily from the Arabian Shield granite rocks (Al-Sayari and Zotl, 1987).

Unfortunately, the dune sand cannot be used as a fill material because of its cohesionless nature that makes it difficult to compact. Therefore, adding a cementing agent (stabilization) is highly recommended (Aiban, 1994).

2.4.2 Marl

Marl or marlstone is defined as a sedimentary rock or a geological layer that is formed due to the deposition of calcareous materials which often exist near shorelines (Fookes & Higginbottom, 1975). Marl soil is formed due to the weathering of these rocks and due to this process, the chemical composition of the marl may vary from place to another and, thus, it may have different engineering properties. However, the presence of carbonate minerals is always expected, whether at small or large percentage (Aiban et al, 1998).

Many studies were carried out to stabilize and modify the geotechnical properties of marl thereby reflecting the importance of such a soil in eastern Saudi Arabia (Aiban et al. 1998; Al-Amoudi et al. 2017). Moreover, marl and clay are both used to remove heavy metals from aqueous solutions and as lining materials for landfills (Stefanova, 2001; Bellir et al, 2005). Therefore, the study of different contaminants on the geotechnical and chemical properties of such types of soil is exigently needed.

2.5 Stabilizers

2.5.1 Limestone Powder (LSP)

LSP is also known as limestone dust and crusher fines. It was obtained from the quarrying operations. It contains large amounts of lime and good amount of silica, depending on the parent rocks (Okagbue and Yakubu, 2000). It is considered as a waste material and poses both disposal and environmental problems. Due to the presence of lime and silica in LSP, it has been used as a cementitious material in producing concrete (Heikal et al, 2000; Dhir et al, 2007; Ahmad et al, 2014). Further, the potential to use this material to improve the geotechnical properties of soils has been assessed by many investigators including few studies at King Fahd University of Petroleum and Minerals (Okagbue and Yakubu, 2000; Banaimoon, 2013). In this research, LSP was obtained from a natural quarry in Abu Hadriyah, eastern Saudi Arabia. The LSP used in this research was used in a previous study (Najamuddin, 2011). The Chemical composition is shown at Table 2.3.

Table 2.3: Chemical Compositions of LSP (Najamuddin 2011)

Compound	Weight (%)
SiO_2	11.79
CaO	45.7
Al_2O_3	2.17
Fe_2O_3	0.68
MgO	1.8
K_2O	0.84
Na_2O	1.72
Na_2O (Equiv.)	2.27
LOI*	35.10

*LOI: Loss on ignition

2.5.2 Cement Kiln Dust (CKD)

CKD is defined as the fine particulate material that is being emitted from the cement kilns in order to prevent the development of excessive amount of salts in cement kilns (Daous, 2004). CKD is captured by the air pollution control system in cement plants. According to the Federal Highway Administration report (1998), part of this CKD is recycled and used again as a raw feeding material while the other part is considered as an industrial waste.

CKD is rich in lime and generated as a waste material in a huge quantity from cement factories as mentioned above. Further, CKD poses the same problems of disposal and environmental pollution. The quantity of CKD generated from a cement factory is found to be around 6 to 7% of the mass of cement produced depending on the raw material (Al-Refeai et al, 1999). In Saudi Arabia, around 61.2 million tons of cement is produced annually (Riyadh Capital, 2016) resulting into a generation of around 3 million tons of

CKD per year. It was estimated that the annual production of CKD around the worlds is about 30 million tons (Dyer et al, 1999). Table 2.4 presents, numerically, a comparison between the chemical compositions of CKD that was used by other researchers (Peethamparan et al, 2008) and the CKD that was considered for this research (Najamuddin 2011).

It was reported that stabilizing soil contaminated by organic chemicals using CKD will improve the soil's engineering properties. About 10% of CKD by dry weight of the soil was used (Amadi et al, 2012). The use of CKD in stabilizing the sabkha soils in Saudi Arabia has been explored with positive results (Al-Amoudi et al, 2006; Shabel, 2006). CKD is also found to be advantageous in producing mortar and concrete due to its cementitious properties (Al-Aghbari and Dutta, 2008; Maslehuddin et al, 2009; Ahmad et al. 2014). A previous study was conducted at KFUPM showed that stabilizing the oil-contaminated soil using CKD will enhance the mechanical properties of the soil (Banaimoon, 2013). According to the Portland Cement Association (2008), the CKD that was utilized for stabilization/solidification of contaminated soil is nearly 213,675 tons (that is about 18.42% of the total produced CKD amount). The CKD that was selected for this research was obtained from Arabian Cement Company in Jeddah, Saudi Arabia.

Table 2.4: Chemical Compositions of CKD (weights in %)

Compound	Peethamparan et al. 2008				Najamuddin 2011
	CKD-1	CKD-2	CKD-3	CKD-4	CKD-Jeddah
SiO_2	12.18	16.42	11.91	15.39	17.1
Al_2O_3	4.24	3.62	2.17	4.66	4.24
TiO_2	0.22	0.23	0.15	0.57	0.34
P_2O_5	0.08	0.09	0.09	0.09	0.12
Fe_2O_3	1.71	2.31	2.08	2.34	2.89
CaO	46.24	55.00	46.05	37.35	49.3
MgO	1.24	2.68	2.20	2.10	1.14
Na_2O	0.51	0.17	0.33	0.81	3.84
K_2O	4.89	2.89	1.43	7.00	2.18
Na_2O equiv	3.72	2.05	1.27	5.36	5.27
SO_3	14.62	12.69	4.21	5.80	3.56
Cl	0.59	0.74	0.35	3.26	6.9
LOI @ 750	14.22	3.92	29.63	27.65	15.8

2.6 Contaminants

2.6.1 Crude Oil

Crude oil is the source of petroleum products. It exists naturally and can be found in geological formations. It is the result of decomposition of animal and plants that are buried beneath the ground and have been subjected to high heat and pressure (EIA, 2017). It can be obtained by drilling and extraction from different geological formations. Through a specific process, which is called "fractional distillation", crude oil is converted to different products such as diesel, gasoline, kerosene, etc. It should be noted that there are different types of crude oil with different sulfur content and API gravity (American Petroleum Institute gravity). In our research, the Arab light crude oil was obtained from Saudi ARAMCO and was used in this investigation. Table 2.5 displays the initial properties of this crude oil that was tested at the Research Institute, KFUPM.

Table 2.5: Characteristics of Arab Light Crude Oil

Property	Value
API gravity	33.4
Specific gravity	0.8575
Total sulfur weight	1.7900
Total nitrogen weight	0.0980
Pour point, ^{O}F	-30.0
Viscosity at 70 ^{O}F	10.20
Viscosity at 100 ^{O}F	6.25

2.6.2 Diesel:

Diesel is one of the crude oil products that is formed during distillation process (Figure 2.3). It is used for engines at which fuel ignition starts by pressurizing inlet air, then injection of fuel (EIA, 2017). The diesel used in this research was obtained from the petrol stations in Al-Khobar, Saudi Arabia.

2.7 Experimental Evaluation of Stabilization/Solidification Treatment

As was mentioned in Section 2.2.1, there are specific tests required to evaluate the effectiveness of S/S treatment. Some of these tests are physical while others are chemical. The effectiveness regarding the physical properties (UCS, CBR and permeability) was based on specific requirements (pavement structure) so that we can decide if the treated soil would be effective as a pavement material.

2.7.1 Unconfined Compressive Strength (UCS)

UCS is considered as the simplest and easiest test performed to examine the shear strength of cohesive soils. The load is applied on soil sample without any lateral support or confinement (Liu and Evett, 2009). For pavement materials, there are minimum requirements to consider the stabilized soil as being accepted as a pavement material. These requirements are presented in Table 2.6 (ACI Committee, 1990).

Table 2.6: UCS Requirements for Pavement Design (ACI Committee, 1990)

Layer	Minimum UCS after 7-days Curing (kPa)	
	Rigid Pavements	Flexible Pavements
Base	3,450	5,175
Sub-base	1,380	1,725

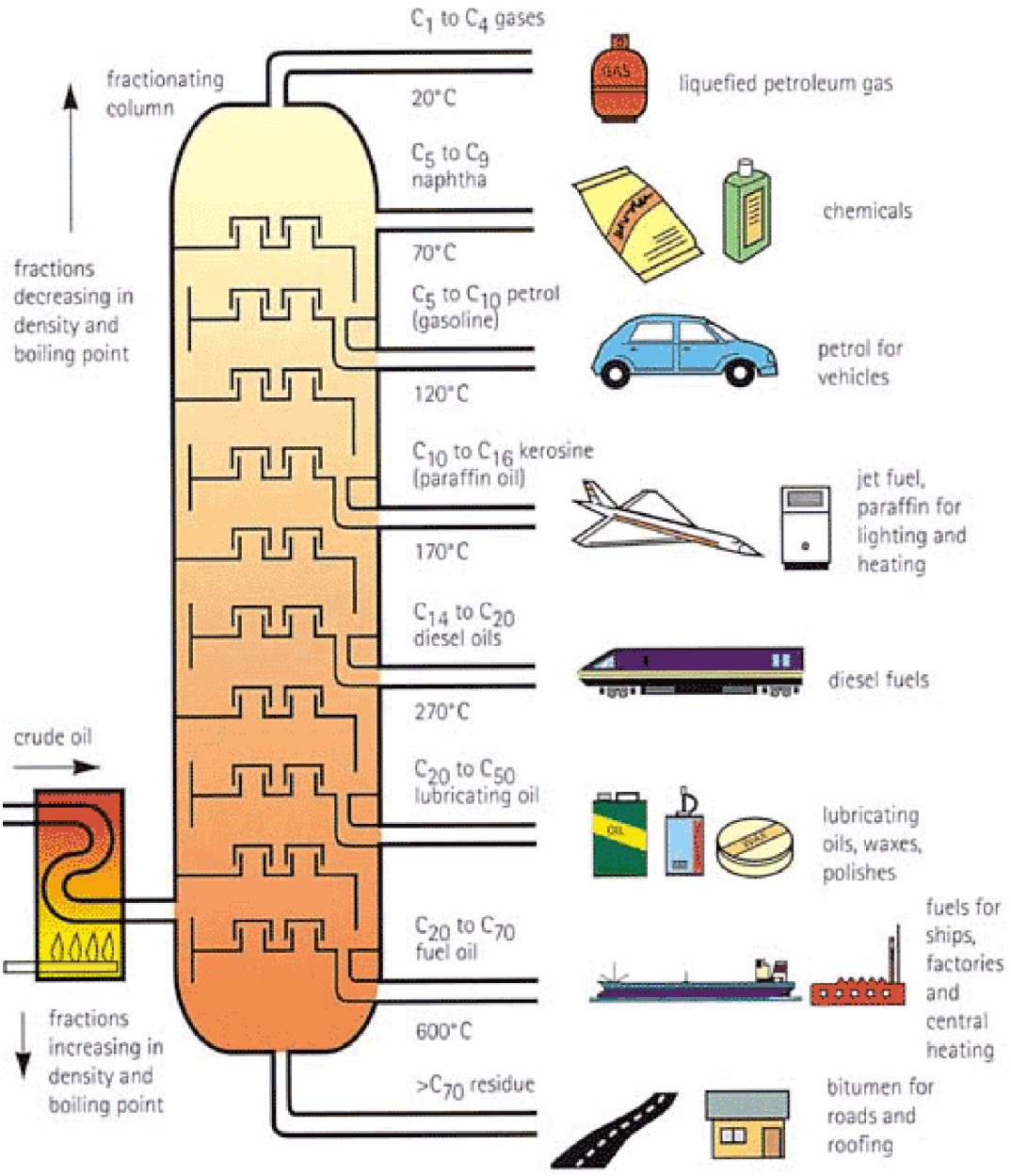


Figure 2.3: Distillation Process of Crude Oil (Odom, 2017)

2.7.2 California Bearing Ratio (CBR)

CBR test is primarily used to determine whether the soil will be suitable for pavement layers (sub-grade, sub-base and base). It helps give an indication of the soil strength for both flexible and rigid pavements (Liu and Evett, 2009). In this test, a piston with a known end area is used to penetrate the soil sample under a specific load rate. Following the standard test is essential since this test has many limitations due to its arbitrary condition (Yoder and Witczak, 1975). Table 2.7 displays the CBR values for different pavement layers (Asphalt Institute, 1970)

Table 2.7: CBR Values for Different Pavement Layers for Flexible Pavements (Asphalt Institute, 1970)

CBR %	Rating	Layer
0-3	Very poor	Sub-grade
3-7	Poor to fair	
7-20	Fair	Sub-base
20-50	Good	Base or sub-base
> 50	excellent	base

2.7.3 Hydraulic Conductivity (Permeability)

Permeability of the soil gives an indication of the denseness of soil structure and the volume of voids in a soil sample. It refers to how much a fluid can pass through the soil at a specific amount of time (Liu and Evett, 2009). The test follow Darcy's law for flow. As was discussed in Sections 2.1 and 2.2.2, the permeability of soil contaminated by oil will be affected with increasing the oil content which will affect the performance of the soil (Al-Sanad et al, 1995; Al-Rawas, 2005; Khamehchiyan et al, 2006; Amadi et al,

2012). Hence, calculating the permeability of the soil before and after treatment is essential to study the effectiveness of S/S treatment. According to USEPA requirement, the stabilized soil permeability should be within the range 10^{-4} to 10^{-8} cm/sec or lower by two orders from the surrounding soil (USEPA, 1989).

2.7.4 Toxicity Characteristics Leaching Procedure (TCLP)

This test is required to determine the presence and mobility of contaminants (both organics and inorganics) by simulating what happens in landfills when water or any other fluid passes through a soil (LaGrega et al, 2001). According to USEPA, the TCLP test is meant to decide whether the soil is hazardous or not so that it can be treated (Qian et al, 2006). The test follows the USEPA 1311 method for both types of wastes (liquid or solid).

The TCLP test measures the concentration of heavy metals in the contaminated soil by adding a specific extraction solution that is selected based on the acidity of the soil. The extraction solution is added to the soil and the mixture is agitated for 18 hours at 30 rpm speed. Then, the solution is filtered and analyzed for the heavy metals.

In our current study, the soil was tested before and after treatment to evaluate the effectiveness of S/S treatment. Contaminants detected by the TCLP test should have minimum concentrations that they should not exceed. Otherwise, the soil will be considered as hazardous, which means the S/S treatment failed. The minimum requirements of heavy metals is presented numerically in Table 2.8 (USEPA, 1998).

2.7.5 Total Petroleum Hydrocarbons (TPH)

To determine the number and content of hydrocarbon compounds that are present in the soil samples, the TPH test was performed. Although the amount of diesel and crude oil should have been known in advance, it is better to define the measurable amount of petroleum-based hydrocarbons in the soil in order to know whether the contamination level is high, medium or low. The samples of the test are prepared according to the USEPA Method 3545 and the analysis is carried out according to USEPA Method 8015C.

In this study, the soil samples were mixed with a specific solvent to remove all the hydrocarbons (Hexane:Dichloromethane) and the solution was left for 24 hours before extraction. After extraction, the solution is analyzed and the TPH is measured.

2.7.6 Polycyclic Aromatic Hydrocarbons (PAH)

One of the main pollutant groups that should be taken into account are the polycyclic aromatic hydrocarbons (PAHs). They are defined as organic compounds that are formed due to partial burning of petroleum products. They are mostly colorless and considered as highly toxic materials (Abdel-Shafy and Mansour, 2016). These compounds consist of two or more fused-benzene rings, some examples are naphthalene, pyrene, benzo(b)fluoranthene, etc. (Wcislo, 1998).

The procedure at which these compounds were measured during this study is similar to that of TPH analysis, where a specific solvent (Hexane:Dichloromethane) was added to the soil and left for 24 hours. After that, the solution was extracted and analyzed to

measure the PAHs. Table 2.9 shows numerically the PAH Limits provided by the Canadian Council of Ministers of the Environment, 2010

2.7.7 XRD Analysis

X-ray diffraction (XRD) is one of the most advanced techniques that is being used to study the micro-structure of the soil (Mitchell and Soga, 2005). X-ray analysis helps in identifying the chemical compositions of the material under study. Taking this into account, new products resulted from stabilization might be detected which helps in studying the changes in the micro-structure. Studying the effects of oil products on the micro-structure of soil is very instrumental to gain knowledge about the behavior of soil particles and how the coating of these particles by oil will affect the overall geotechnical properties of the soil (Rehman et al, 2007). In this research, some selected samples were studied to evaluate the effect of contaminants and stabilizers on the micro-structure of both sand and marl.

2.7.8 SEM/EDS Analysis

Scanning electron microscope (SEM) is used to have an insight images of the materials under consideration. Unlike the XRD, the SEM uses electron beam instead of X-ray photons (Mitchell and Soga, 2005). In addition to the SEM, energy-dispersive detector (EDS) analysis is applied with SEM at the same time on the same samples. The EDS helps identify the different elements that form from S/S of soils contaminated by petroleum products. It is to be noted that the same samples that were tested by XRD were analyzed using both SEM and EDS.

Table 2.8: Heavy Metals Minimum Allowable Values (USEPA, 1998)

Contaminant	Permissible Level (ppm)
As	5
Ba	100
Cd	1
Cr	5
Pb	5
Hg	0.2
Se	1
Ag	5

Table 2.9: PAH Limits (Canadian Council of Ministers of the Environment, 2010)

	Land Use (ppm)			
	Agricultural	**Residential**	**Commercial**	**Industrial**
Anthracene	2.5	2.5	32	32
Benzo (a) pyrene	20	20	72	72
Naphthalene	0.013	0.013	0.013	0.013
Benzo (a) anthracene	0.1	1	10	10
Benzo (b) fluoranthene	0.1	1	10	10
Benzo (k) fluoranthene	0.1	1	10	10
Pyrene	0.1	10	100	100

CHAPTER 3

EXPERIMENTAL WORK

In this research, the experimental work was carried out at six main steps. First, the materials were collected. These materials included the soils, contaminants and stabilizers. Secondly, the soils were characterized using basic geotechnical tests (e.g., sieve analysis, standard Procter test, etc.) plus the SEM, XRD, TPH, PAH and TCLP tests. After that, the soils were contaminated by both the diesel and crude oil. After contamination, the contaminated soils were characterized to assess the changes in the geotechnical, micro-structure and environmental properties. Then, the contaminated soils were stabilized using the selected stabilizers. The characteristics of the stabilized soil were evaluated using UCS, permeability and TCLP to select the optimum mixes. XRD and SEM tests were carried out to evaluate the changes in the micro-structure of the contaminated soils. Finally, the obtained results were evaluated and analyzed to obtain valuable relationships. The last part was discussed in the following chapter (Chapter 4).

3.1 Materials

3.1.1 Soils

For this research, sand and non-plastic marl were selected because, as discussed in Chapter 2, they are the commonly soil types used for engineering applications in eastern Saudi Arabia. Figures 3.1 and 3.2 shows graphically the locations from which the soils were collected. The dune sand was collected from a location near KFUPM Beach, while the marl was collected Al-Yamama Company (working on a project at KFUPM).

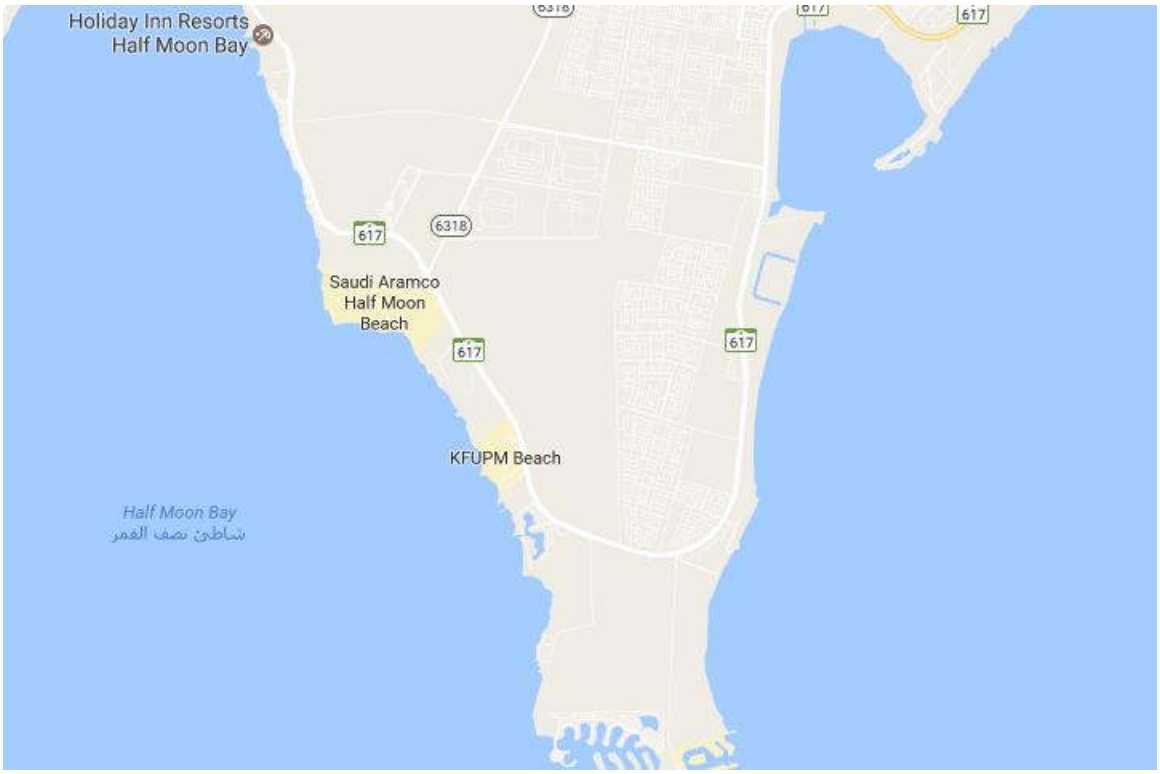


Figure 3.1: Location of the Sand Used in the Current Research

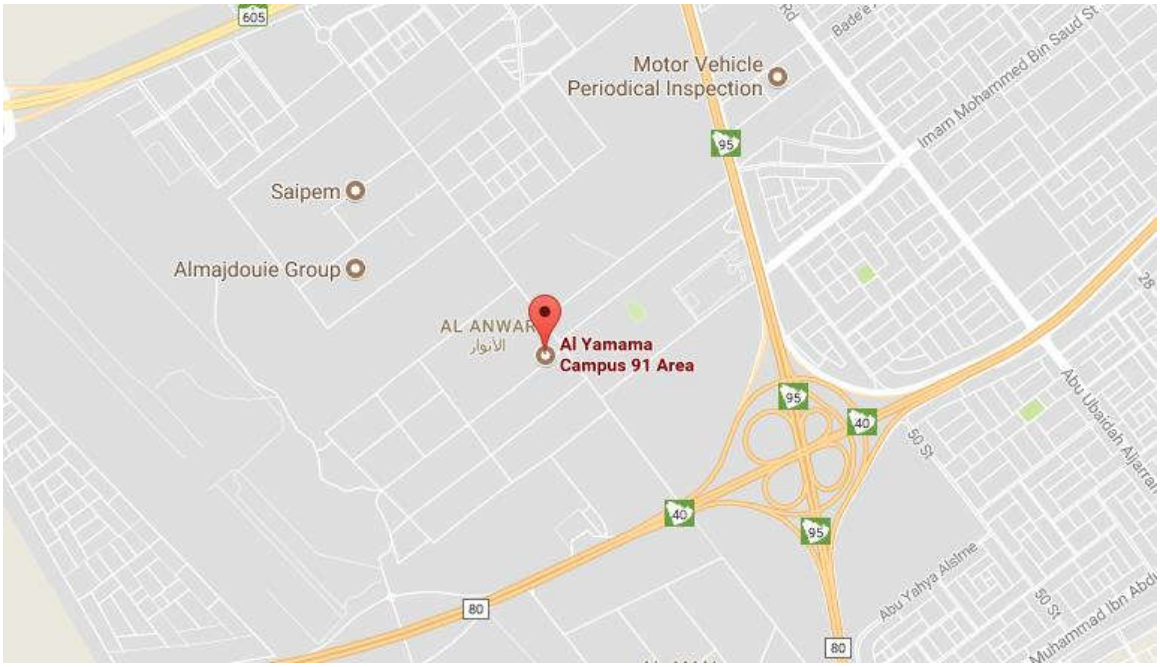


Figure 3.2: Location of the Marl used in this Research

3.1.2 Contaminants Selection and Collection

As was discussed in Chapter 2, many researches were conducted to study the effect of oil-contamination on the geotechnical properties of soil. Many researchers have used the crude oil (Al-Sanad et al, 1995; Rehman et al, 2007; Alhassan and Fagge, 2013; Oluremi et al, 2015), while others used different types of contaminants, such as kerosene (Vipulanandan and Elesvwarapu, 2008; Rasheed et al, 2014) and motor oil (Nazir, 2011).

Therefore, the crude oil and diesel were selected in this program. The crude oil was selected since it is the most common type of oil-contamination and many accidents happen with oil tankers (ITOPF, 2015), while the diesel was selected to assess the effects of one of the oil products to make a valuable comparison between the effects of crude oil and its products. The diesel was brought from a petrol station in Dammam, Saudi Arabi, while the crude oil was collected from Saudi Aramco company. Figure 3.3 shows both the diesel and crude oil.

3.1.3 Stabilizers Collection

Three types of stabilizer were used in this research. They are ordinary Portland cement (OPC), cement kiln dust (CKD) and the limestone powder (LSP). OPC was bought from Saudi Cement Company in Dammam city. The CKD was obtained from the Arabian Cement Company, Rabegh plant, while the LSP was brought from Abu Hadriyah quarry (see Figure 3.4).

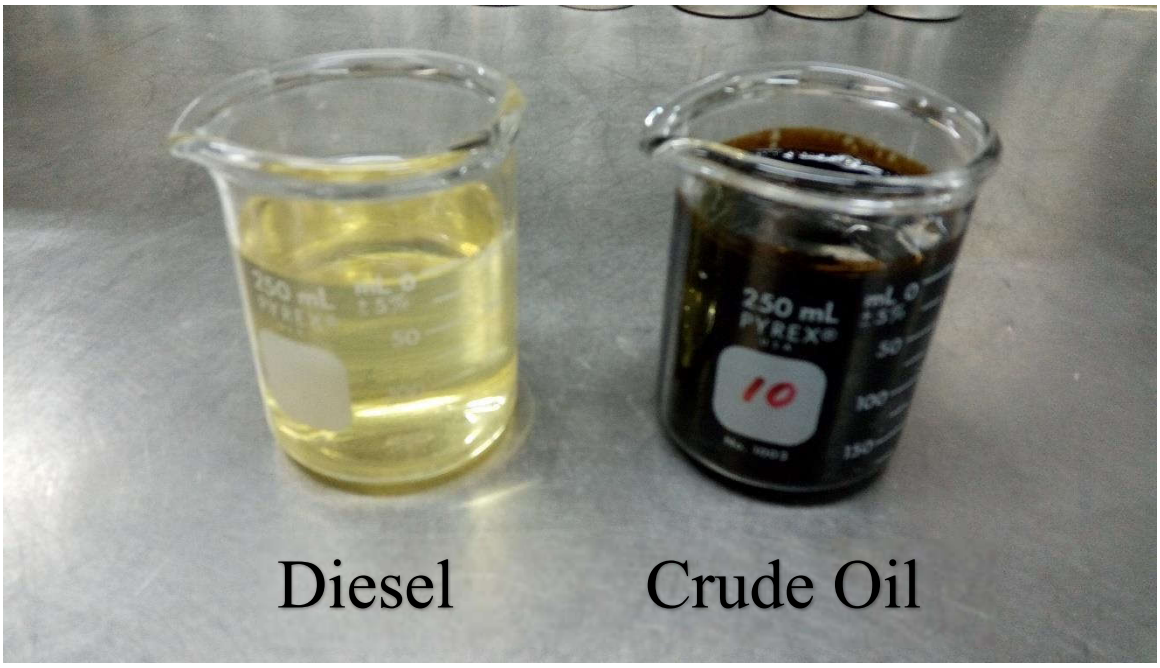


Figure 3.3: Diesel and Crude Oil Used in This Study

Figure 3.4: Stabilizers Used in This Research

3.2 Soil Characterization

3.2.1 Soil Preparation

After collecting the soil, it was pulverized using a plastic hammer. This was done to insure the removal of all moisture during the drying process. Then, the soils were left to be air-dried outside the laboratory for one week and, thereafter, they were oven-dried for 24 hours at 110 º C. Then, the soil was kept inside barrels inside the laboratory until testing.

3.2.2 Specific Gravity

After preparation of the soil, both the sand and marl specific gravity were determine using the standard method (ASTM D854, 2014). The soil samples were dispersed by adding about 100 ml of water to 100 g of soil and the mixture was blended using a mechanical blender. Therefore, the soil particles were dispersed and then placed inside the 500-ml pycnometer and the test was carried out. The average specific gravity was 2.63 and 2.85 for sand and marl, respectively.

3.2.3 Sieve Analysis and Hydrometer

Both soil samples were tested to determine their grain sizes using the standard sieve and hydrometer analysis according to the ASTM D422 standard. For marl soil, a significant amount of fine particles (passing sieve No. 200) was obtained (about 47% of total soil sample). Therefore, performing the hydrometer analysis for the marl was essential. It should be noted that both the dry and wet methods were conducted to insure removal of all attached particles.

3.2.4 Atterberg Limits (Marl)

Marl soil was tested for its Atterberg limits. The test was conducted based on the ASTM D4318 standard. A liquid limit of 21.84% was obtained, while plastic limit was found to be 21.25%. Therefore, a plasticity index of 0.59% was obtained which classify this soil as non-plastic.

3.2.5 Relative Density (Sand)

Due to the cohesionless behavior of sand, both the maximum and minimum dry density were determined using the relative density test. The test was performed using the vibratory table as per the ASTM standard (ASTM D4253, 2016). First, the minimum dry density was measured by pouring the sand using a funnel inside the standard mold (Figure 3.5-a). Then, the weight was determined and thus the minimum density was measured. For the maximum dry density, the soil was poured in three layers inside the mold that was then transferred to the vibratory table. A standard weight was placed at the top of the soil (See Figure 3.5-b) and then the mold was vibrated for about 10 minutes. The weight and change in volume of the soil after vibration was recorded and thus the maximum dry density was determined. This process was repeated three times (for both maximum and minimum density) and the average value was taken.

3.2.6 Standard Proctor Test (Marl)

The maximum dry density and optimum moisture content of the marl was measured using the standard Proctor test (ASTM D698, 2012). For this test, to insure obtaining the same compaction effort, a mechanical compaction machine was used (see Figure 3.6-a). The soil samples were prepared and mixed with the water using the mechanical mixer, as shown in Figure 3.6-b.

a)

b)

Figure 3.5: Relative Density Test Apparatus: (a) Standard Mold; and (b) Compaction Weight

a) b)

Figure 3.6: Compaction Test Apparatus: (a) Mechanical Compactor; and (b) Mechanical Mixer

3.2.7 Hydraulic Conductivity (Permeability)

Permeability was assessed using both the constant and falling head methods for sand and marl, respectively. This was done according to the ASTM D2434. Both soil samples were prepared at their maximum dry density by placing the samples at three layers and tamping them using a small hammer to achieve the maximum possible density. The test was repeated three times and the average value was taken. The setup for the permeability test is shown in Figure 3.7.

3.2.8 Unconfined Compressive Strength (Marl)

Samples used for the unconfined compressive strength (UCS) were prepared using a miniature mold that was used in a previous study (Banaimoon, 2013). The mold had a 1.5-inch (25.4 mm) diameter and 3-inch (50.8 mm) height (as shown in Figure 3.8) in order to get a height to diameter ratio of 2, as recommended by UCS test standard (ASTM D2166, 2016). Using this small mold has helped in reducing the amount of the soil needed for the UCS soil since there was a large number of samples that were prepared in this research.

During this research, two UCS samples were prepared for each test and the average value was determined to minimize the uncertainty in calculating the UCS value. After the preparation of each sample, it was sealed inside a double plastic bag in order to maintain the moisture and allow the sample to be cured for the proposed period (7, 28 and 90 days).

Figure 3.7: Permeability Test Setup (Falling Head)

Figure 3.8: Miniature Compaction Mold (UCS Test).

3.2.9 XRD Analysis

Both sand and marl samples were prepared for the XRD analysis. To have clear and more reliable results, the samples had to be prepared in powder form (very fine particles), therefore, the soils passing sieve No. 200 were considered for the study. The samples were placed on small circular plates (5 cm diameter) and placed inside the XRD machine (X-Ray Diffractometer, Ultima IV, Rigaku).

The test ran for 30 minutes and the results were analyzed. Readings of 2θ angle and the intensity of the X-ray were analyzed and the peak values were compared to the chemical compositions in the data base. The samples were analyzed at a 2θ range from zero to 80^{o}.

3.2.10 SEM and EDS Analysis

The same samples used for XRD analysis were also used in the SEM and EDS analysis. The samples were prepared by placing them on small plates and coating them with platinum (Pt) in order to improve the emission of secondary electrons and improve the edge resolutions of the images (Leica Microsystem, 2013). It should be noted that the platinium has finer particles and thus it is suitable for higher magnifications (Nanoandmore, 2017).

Then, the samples were placed inside the SEM machine (X-Max device, Oxford Instrument). Different images were taken and the EDS analysis was carried out immediately to measure the concentrations of the elements.

3.3 Soil Contamination

3.3.1 Selection of Contamination Dosages

Following the previous researches that were conducted on the contamination of soil by petroleum products and crude oil, as mentioned in Section 2.2, three dosages were selected for both contaminants. These are 2.5%, 5% and 10% by dry weight of the soil.

3.3.2 Contamination Process

To achieve proper contamination of the soil, it has been commonly reported that the soil should be contaminated with the required percentage of the contaminant and then to be air dried for nearly a week to assure full absorption of the contaminant by the soil (Amadi & Eberemu, 2012; Vipulanandan & Elesvwarapu, 2008; Habib-ur-Rehman et al, 2007). Therefore, both sand and marl were contaminated by diesel and crude oil using the three suggested dosages (2.5, 5 and 10% by dry weight). The dry soil was mixed with the diesel and with the crude oil using the mechanical mixer for 10 minutes. After that, the soil was left for one week to allow the full absorption of the contaminants by the soil. Figures 3.9 and 3.10 show the contaminated soil immediately after mixing.

Figure 3.9: Soil Contaminated by Crude Oil after Mixing

Figure 3.10: Soil Contaminated by Diesel after Mixing

3.4 Characterization of the Oil-Contaminated Soils

3.4.1 Specific Gravity

Following the previous researches that were conducted on the contamination of soil by petroleum products and crude oil mentioned in Section 2.2, three dosages were selected for both contaminants. These are 2.5%, 5% and 10% by dry weight of the soil. The specific gravity at each dosage was determined according to the ASTM D854 (2014). It should be noted that the effect of contamination on the specific gravity was not inspected by many researchers. Rasheed et al (2014) had studied the effect of kerosene and gasoline on the specific gravity of a sandy soil. Their results have indicated a reduction in the specific gravity at 7.5% contamination level (by dry weight of the soil) as compared to the uncontaminated soil (reduction by 5.7% for the case of kerosene contamination and by 13.3% in the case of gasoline contamination).

3.4.2 Grain Size Analysis

At each dosage of the contaminants (for both diesel and crude oil), a representative sample was prepared by oven-drying the soil to the insure removal of any volatile agent or moisture in the soil specimens. Then, sieve analysis test was conducted and the variation in grain size was determined according to ASTM D422 (2007).

3.4.3 Atterberg Limits (Marl)

The soil passing sieve No. 40 was collected for each dosage. Then, Atterberg limits were determined to assess the changes in liquid limit (LL), plastic limit (PL) and plasticity index (PI) due to the contamination according to ASTM D4318 (2010).

3.4.4 Relative Density (Sand)

Since it was difficult to perform the standard Proctor test on the contaminated sand, the relative density test was carried out. The contaminated soil had to be oven-dried and then the test was carried out based on ASTM D4253 standard (as discussed in Section 3.2.5)

3.4.5 Standard Proctor Test (Marl)

In the case of the contaminated marl, the soil was oven-dried and, then, the same procedure discussed in Section 3.2.6 was repeated.

3.4.6 Hydraulic Conductivity (Permeability)

After contamination, the contaminated soil was tested for its permeability using both the constant and falling heads, as mentioned in Section 3.2.7. The soil was compacted inside the mold and then the water was allowed to saturate the samples. After that, the water was collected at a fixed time to insure the flow is regular (constant flow with time). Then, the tests were performed for each dosage three times and the average value was determined.

3.4.7 XRD, SEM and EDS Analysis

The same procedures discussed in Sections 3.2.9 and 3.2.10 were repeated. This time, the contaminated soil had to be oven-dried and, then, the samples passing sieve No. 200 were used for the test. Only the samples with the highest contamination level (10%) were tested to assess their micro-structure.

3.5 Stabilization/Solidification Treatment

As was mentioned in Section 2.3, to evaluate the effectiveness of S/S treatment, a number of tests can be performed in order to evaluate the S/S treatment in terms of physical and chemical changes. Those tests include the following (USEPA, 1995):

- Unconfined compressive strength;
- Permeability; and
- TCLP.

The unconfined compressive strength was performed on the samples at their maximum dry density and optimum moisture content. Hence, the contaminated soil was tested using the standard Proctor test to determine both the maximum dry density and optimum moisture content to prepare the UCS samples.

3.5.1 Compaction Characteristics of Stabilized Soil

As mentioned in Section 2.5, three types of stabilizers were collected to be used in S/S treatment. The contaminated soil was oven-dried for 24 hours and mixed with the different stabilizers at the proposed proportions (see Table 3.1). After that, the standard Proctor test was carried out to determine the maximum dry density and optimum moisture content.

3.5.2 Unconfined Compressive Strength (UCS)

After determining the maximum dry density and optimum moisture content, the UCS samples were prepared using the miniature compaction mold and wrapped with plastic sheet for curing. After 7 days, the samples were tested to determine the UCS in order to decide whether this mix would pass the minimum strength requirement for S/S samples

and pavement design. Figure 3.11 shows part of the UCS samples during the curing period.

Table 3.1: Proposed Mixture for Contaminated Soil Treatment

Stabilizers Dosage
Untreated
2.5% OPC
5% OPC
7.5% OPC
2.5% OPC + 10% LSP
2.5% OPC + 20% LSP
2.5% OPC + 40% LSP
2.5% OPC + 5% CKD
2.5% OPC + 10% CKD
2.5% OPC + 20% CKD

3.5.3 Permeability

Following the UCS test, permeability test was performed on the samples that passed the USEPA requirements. Since there was a large number of samples, the worst scenario (10% contamination by the diesel and crude oil) was considered for the permeability test. Because of the presence of the stabilizers (OPC, CKD and LSP), it was expected to have very low permeability and, therefore, the falling head test was used to assess the permeability of the mixes.

3.5.4 California Bearing Ratio (CBR)

As was discussed in Section 2.7.2, soaked CBR test was carried out on selected samples that passed the ACI requirements for minimum UCS (7-days of curing shown in Table 2.6). The test was carried out according to ASTM D1883 standard. CBR samples were

prepared and sealed using plastic sheets and cured for 3 days (air-curing). After that, the samples were immersed in water for 4 days after removing the seal to simulate the worst conditions that might happen in the field. Then, the specimens were tested using the same UCS testing machine. The load was applied at a low rate (1.3 mm/min) and the penetration was recorded along with the loading. The results obtained (penetration and loading) were analyzed and the CBR values were calculated.

3.5.5 TCLP Test

After performing the permeability test, the samples that passed both the strength and permeability requirements were considered for the TCLP test. Chosen samples were collected after performing the UCS test. The TCLP test was carried out according to the USEPA 1311 method to detect the heavy metals that might be in the treated soil.

Chosen samples were collected after performing the UCS test. Then, the samples were crushed to obtain the size required by the 1311 method (<9.5 mm). After that, about 5 grams of each mix was mixed with 96.5 ml of distilled water then it was agitated using magnetic agitator (See Figure 3.12). After agitation, the pH of the mixes was measured using a pH meter with ±0.05 accuracy. The pH for all samples was found to be more than 5 (alkaline solutions). Therefore, 3.5 ml of 1N HCL was added to the mixes and they were heated to 50 ^{o}C and the pH was measured again. The pH was still found to be larger than 5 and, therefore, the extraction fluid was prepared by dilution of 5.7 ml of glacial CH_3CH_2OOH with distilled water to a volume of 1 liter.

10 grams of each soil sample was added to 200 ml of the prepared extraction fluid inside a fiberglass container. After preparing the samples, they were placed in a mechanical

rotary agitator that runs at about 30 rpm for 18 hours (See Figure 3.13). After 18 hours, the samples were filtered using a vacuum filter and the liquid extracts were collected (Figure 3.14).

Since these samples were considered for heavy metals analysis, they had to be acidified (pH < 2.0). Therefore, 3 ml of concentrated nitric acid was added for 25 ml with each TCLP extract. The mix was heated to near dryness (about 3 ml), then another 5 ml of concentrated nitric acid was added and the heating continued for another round. When the mix reached 3 ml, about 10% nitric acid was added and the solution was diluted with distilled water to a volume of 25 ml (which is the amount required for analysis). This solution was analyzed for heavy metals' content using the inductively coupled plasma device (ICP) (USEPA Method 1311, 1992).

3.5.6 TPH Analysis

The test was carried out on the same samples that were considered for TCLP and PAH tests. The preparation of the samples was carried out according to the USEPA Method 3545, where 5 grams of each sample were collected and mixed with 25 ml of Hexane:Dichloromethane solvent. The mixture was left for 24 hours to allow full reaction between the solvent and the hydrocarbons in the soil samples. Then, the resulted solution was collected and another 10 ml of the solvent was added to the remaining sediments inside the flask and was left for another 24 hours, which was thereafter added to the previous solution. The samples were left for about 8 hours to allow the sediments to settle and, then, 1.5 ml was collected from each sample and placed inside a small testing tube. The samples were analyzed according to USEPA Method 8015C using the gas chromatograph mass spectrometer (GCMS) device and the results were recorded.

3.5.7 Polycyclic Aromatic Hydrocarbons (PAH)

The PAH test was carried out on the same solutions that were collected for TPH analysis. 1.5 ml of the solution was placed inside small tubes and the analysis was carried out based on the USEPA Method 8260B using the GCMS device. Figure 3.15 shows the samples used for both TPH and PAH analysis.

3.5.8 Micro-Structural Analysis

Some samples that had passed the strength and environmental (TCLP) requirements were selected to test their micro-structure using the XRD, SEM and EDS analysis. The same procedures discussed earlier in Sections 3.2.9, 3.2.10 and 3.4.7 were repeated and the results were analyzed.

Figure 3.11: Part of UCS Samples, Sealed for Curing

Figure 3.12: Samples Used for pH Analysis

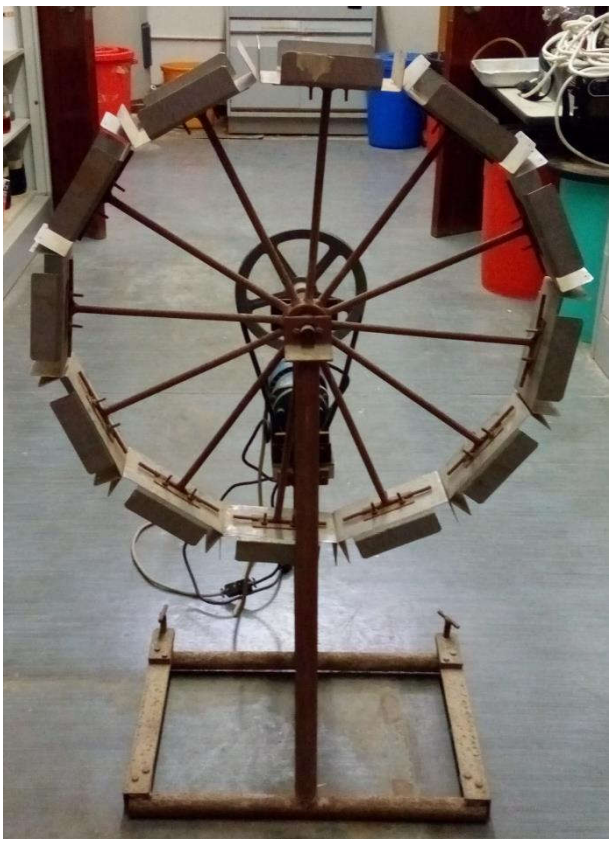


Figure 3.13: Samples Agitator for TCLP Samples Preparation

Figure 3.14: Vacuum Filtration Device for TCLP Test

Figure 3.15: Preparation of Samples for TPH and PAH Analysis

CHAPTER 4

RESULTS AND DISCUSSION

In this chapter, discussion is made on the results of the tests conducted: (i) to characterize the local soils used in the present study, (ii) to assess the effects of the oil-contaminants on the geotechnical, environmental and the microstructural properties, and (iii) to evaluate the performance of S/S treatments of contaminated soils using OPC, LSP and CKD as stabilizers.

4.1 Soil Characterization

4.1.1 Soil Classification and Basic Properties

The results of soil characterization are presented numerically in Table 4.1. Both marl and sand were classified according to the Unified Soil Classification System (ASTM D2487, 2011) and the American Association of State Highway and Transportation Officials (AASHTO) system (ASTM D3282, 2015). The results of sieve analysis for the sand and marl are shown graphically in both Figures 4.1 and 4.2, respectively. As shown in Table 4.1, the sand specific gravity was lower than that of the marl, which might be attributed to the fact that the marl used in this study is mixed with sand since it is being used for pavement constructions. Regarding Atterberg limits, the sandy soil was considered as non-plastic and both the liquid and plastic limits were not determined. In the case of marl, the values of 21.84% and 21.25% were obtained for liquid and plastic limits, respectively, which gives a plasticity index of 0.59%. Therefore, the marl soil was considered as non-plastic marl (Liu and Evett, 2009).

Due to the difficulty in performing the standard Procter test on sand, the relative density test was carried out and a maximum dry density of 18.68 kN/m^3 was obtained which is larger than that obtained in the case of standard Proctor test of the marl (16.54 kN/m^3). This difference in the maximum dry density is attributed to the difference in compaction effort difference between the two tests despite the lower specific gravity of the sand. An optimum moisture content of 18.06% was obtained for the marl.

A higher permeability was observed in the case of sand (2.53×10^{-3} cm/sec) compared to that of the marl (3.4×10^{-5} cm/sec), which was attributed to the higher content of fines for marl. Fine materials tend to decrease the permeability by reducing the voids' volume in the soil and their capability of clogging the voids (Mitchell and Soga, 2005). Testing the marl for its UCS, a value of 95.26 kPa was obtained. Using the values of Atterberg limits and sieve analysis for both soils, the soils were classified as well-graded soil (SW) in the case of sand and clayey soil (SC) for marl. Following the AASHTO classification system, the sand was considered as A-3 soil, which is described as a fine sand and can be used as a subgrade soil. In the case of marl, it was classified as A-4 soil, which is considered as a silty soil and can be used as a subgrade material.

4.1.2 SEM and XRD Analysis

The results obtained through XRD analysis are presented in Figures 4.3 and 4.4. These results indicate that the sand is primarily composed of 98% quartz (SiO_2) and only 2% of calcite ($CaCO_3$). On the other hand, the predominant mineral in the marl soil is dolomite [$CaMg(CO_3)_2$] which form about 53.8% of the marl along with 34% quartz and 12.2% calcite.

Figure 4.3 shows SEM images of sand (100 µm magnification). As shown in Figure 4.3, the sand particles are almost rounded and have smooth surfaces reflecting their cohesionless nature. Similarly, Figure 4.4 shows SEM image of the marl and it can be seen that more roughness on the marl particles surfaces is observed. Also, the large variation in the marl particles increases the interlocking between the particles which may increase the internal friction. Another point to be noted is that there is a large variation between the sizes of the marl particles as compared to those of the sand. This variation was evidenced by the flatter grain-size distribution curves in Figure 4.2 as compared with that of sand (Figure 4.1).

Table 4.1: Summary of Basic Geotechnical Properties of Sand and Marl

Test	Sand	Marl
Specific gravity	2.63	2.80
Liquid limit (%)	-	21.84
Plastic limit (%)	-	21.25
Plasticity index (%)	NP	0.59
Maximum dry density (kN/m^3)	18.68*	16.54
Optimum moisture content (%)	-	18.06
Permeability (cm/sec)	2.53×10^{-3}	3.4×10^{-5}
Unconfined compressive strength (kPa)	-	95.26
Unified Soil Classification System	SW	SC
AASHTO Classification	A - 3	A - 4

*Relative density

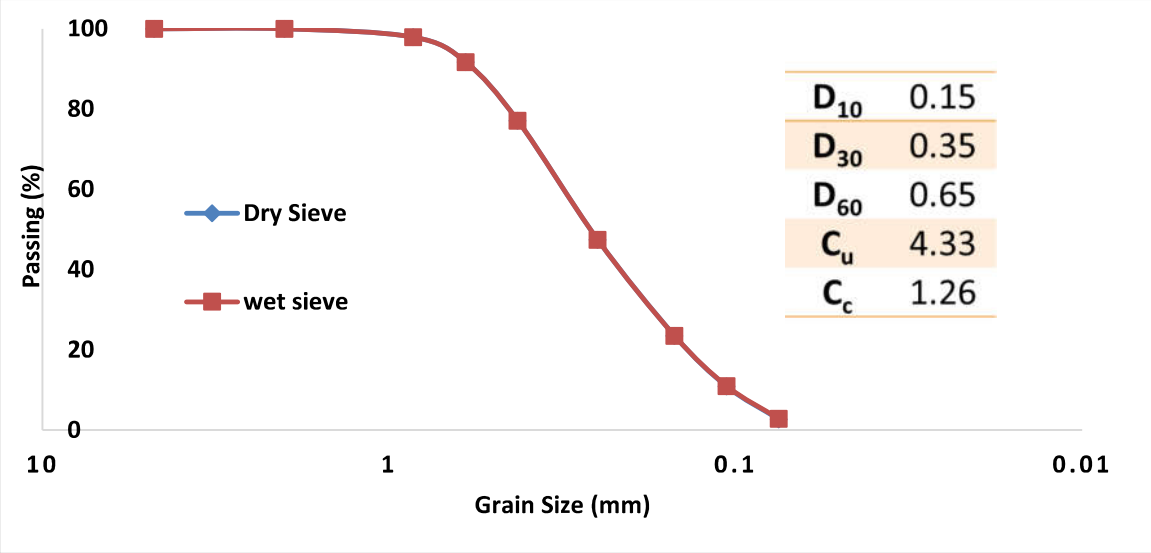


Figure 4.2: Grain Size Analysis of Sand

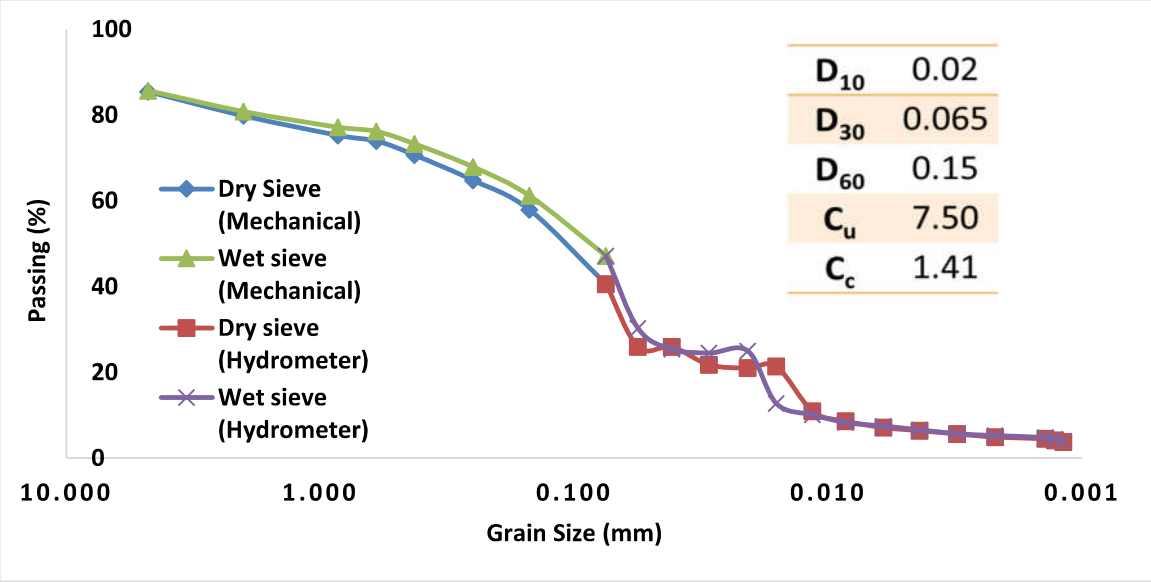


Figure 4.1: Grain Size Analysis of Marl

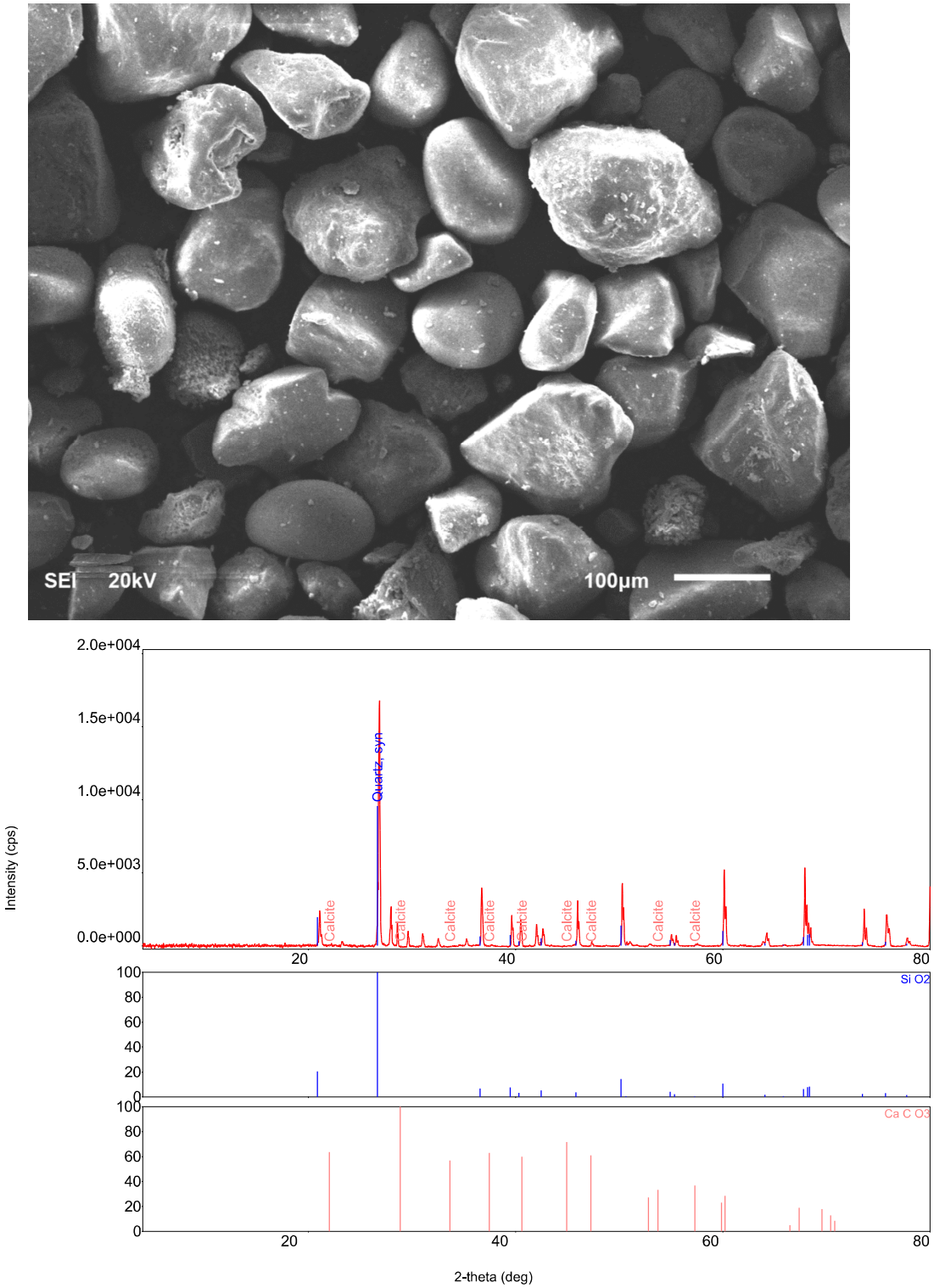


Figure 4.3: SEM Image and XRD Analysis of Sand

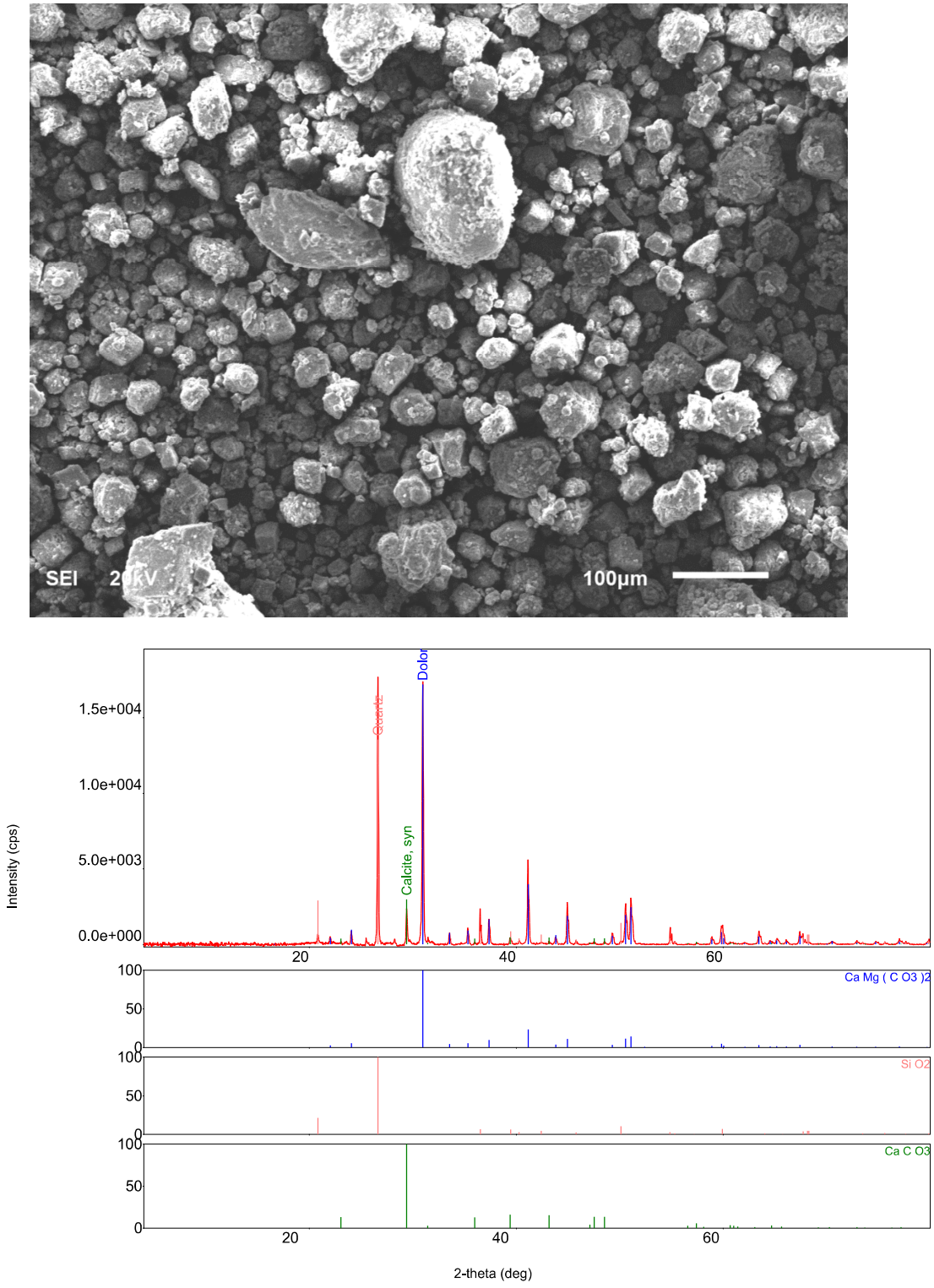


Figure 4.4: SEM Image and XRD Analysis of Marl Soil

4.2 Characterization of Oil-Contaminated Soils

4.2.1 Specific Gravity

The effect of both the diesel and crude oil on the specific gravity of the sand and marl is shown graphically in Figures 4.5 and 4.6. As can be seen from Figures 4.5 and 4.6, the increase in oil content tends to decrease the specific gravity for both sand and marl. This effect is due to the low specific gravity of crude oil (0.8575) and diesel (0.8320) which is much lower than that of sand and marl (2.63 and 2.80, respectively). Therefore, replacing soil particles with lighter materials like crude oil and diesel has decreased the specific gravity of the contaminated soils.

4.2.2 Grain Size Analysis

Figure 4.7 shows the effect of increasing diesel and crude oil content on the grain sizes of sand. The data therein indicate that with increasing the oil content, the particle size is increasing significantly. This increase in the grain size is ascribed to the effect of agglomeration of the particles whereby they are attracted to each other with increasing the oil content (Ijimdiya and Igboro, 2012).

The same behavior is observed in Figure 4.8, whereby the size of marl particles is increasing with increasing the oil content. It is to be noted that this effect is highly noticeable on the part of fine particles (passing sieve No. 40). This may be attributed to the fact that the fine particles are more chemically active and thus they tend to attract and react with other materials thereby attracting more diesel and crude oil to their surfaces, resulting in increasing the particles size (Stegmann et al, 2001).

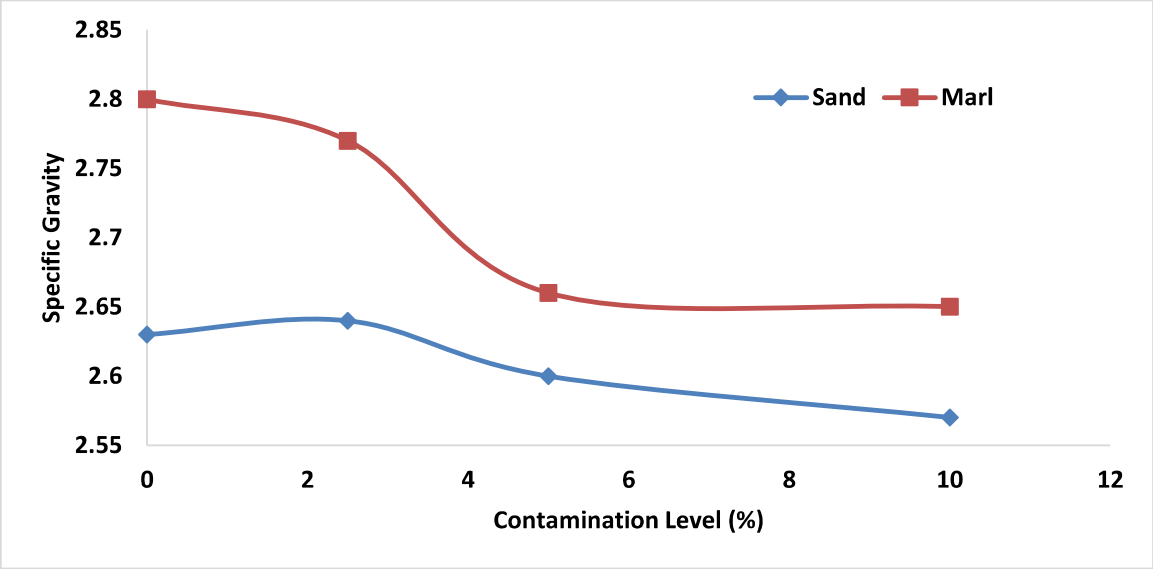


Figure 4.5: Variation of Specific Gravity with Contamination Level by Diesel

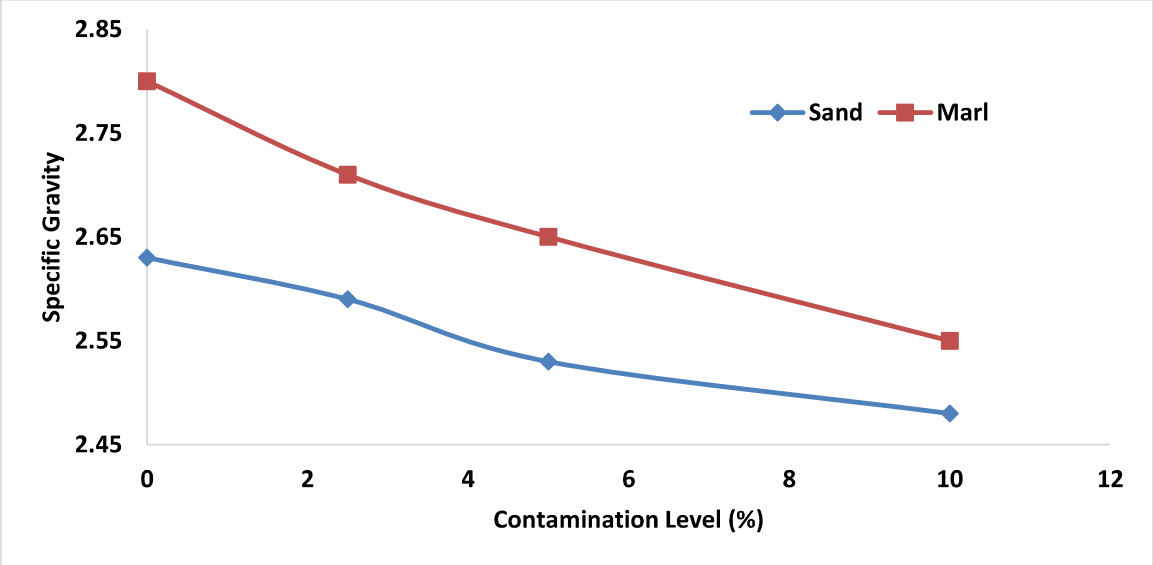


Figure 4.6: Variation of Specific Gravity with Contamination Level by Crude Oil

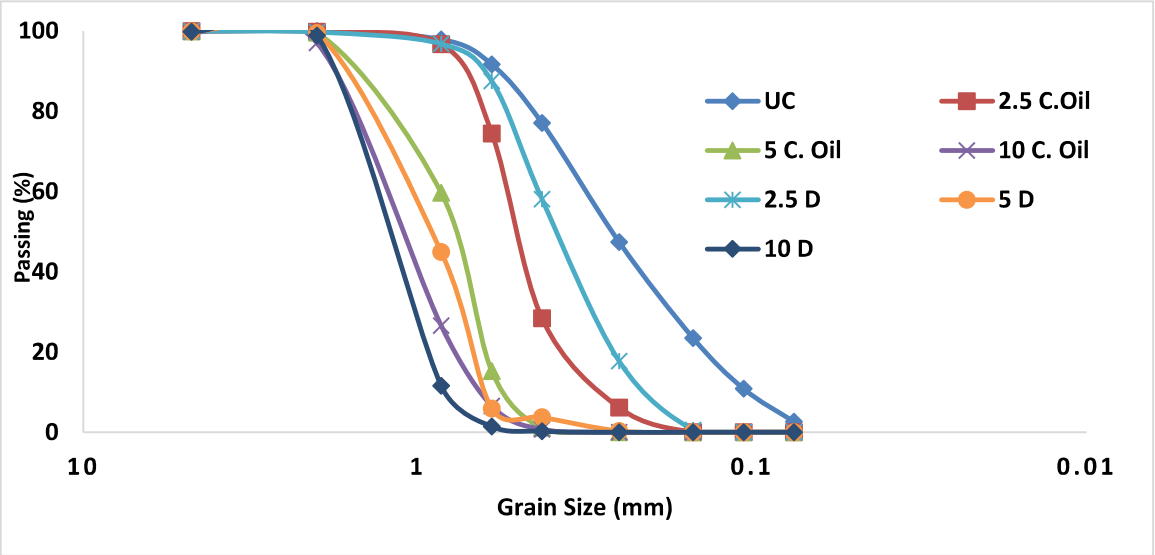


Figure 4.8: Grain Size Analysis of Contaminated Sand

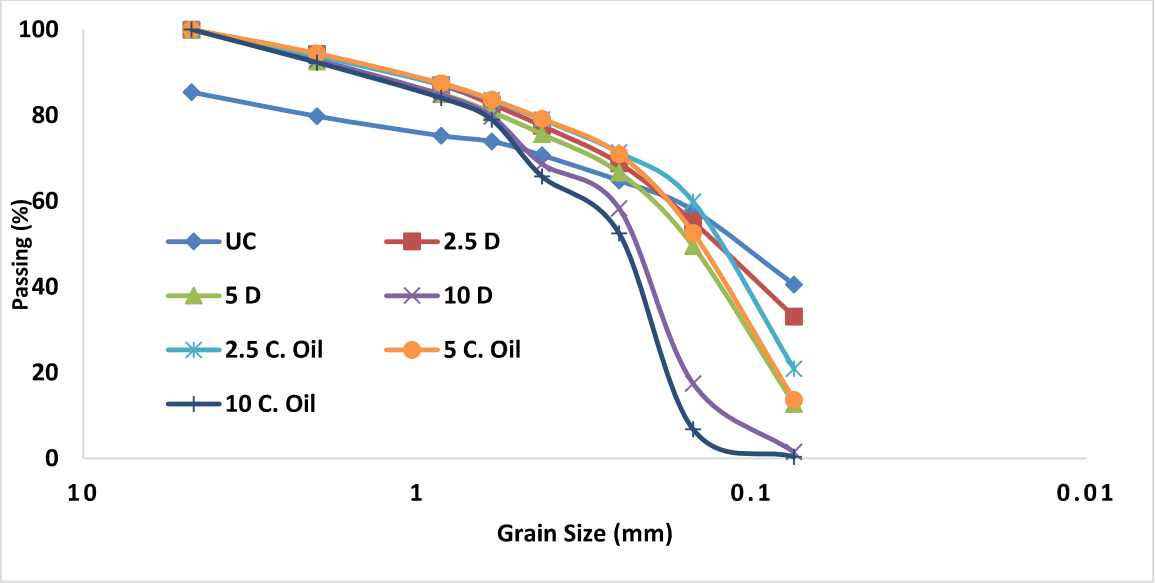


Figure 4.7: Grain Size Analysis of Contaminated Marl

- UC: uncontaminated; D: diesel contaminated; C. Oil: crude oil-contaminated

4.2.3 Atterberg Limits (Marl)

The effect of diesel and crude oil on the liquid and plastic limits and the plasticity index is presented numerically in Table 4.2 and graphically in Figures 4.9 and 4.10. Figure 4.9 shows that increasing the diesel content tends to marginally increase the LL, PL and PI. Comparing the LL of the uncontaminated marl to that of 10% contaminated marl, a significant increase is observed (about 28%), while the plastic limit has increased by 22%. The same behavior was observed by other researchers (Vipulanandan and Elesvwarapu, 2008; Rasheed et al, 2017). Similar behavior is observed in Figure 4.10 with the crude oil contamination but the increase in plastic limit is marginal while the liquid limit is increasing up to 2.5% contamination, thereafter, it started to decrease marginally.

This increase in the liquid and plastic limits could be attributed to the fact that the addition of both diesel and crude oil tend to increase the cohesion between soil particles due to their high viscosity, which will require more water to change the state of soil from certain plasticity to more plastic state (Rehman et al, 2007). As shown in Table 4.2, both diesel and crude oil have increased the plasticity index (added some plasticity to the marl), in a way similar to previous studies (Rehman et al, 2007; Vipulanandan and Elesvwarapu, 2008). It should be noted that the increase in the diesel dosage has increased the plasticity, however, the increase in crude oil has increased the plasticity up to 2.5% contamination and then started to decrease. This means that the diesel effect on the plasticity was more efficient than that of the crude oil.

Table 4.2: Summary of Atterberg Limits for Marl Soil

Contaminant Dosage (%)	Diesel			Crude Oil		
	LL (%)	PL (%)	PI (%)	LL (%)	PL (%)	PI (%)
0	21.8	21.3	0.5	21.8	21.3	0.5
2.5	25.0	21.8	3.2	26.0	20.1	5.9
5	26.0	23.1	2.9	24.0	19.9	4.1
10	31.0	26.0	5.0	23.0	21.6	1.4

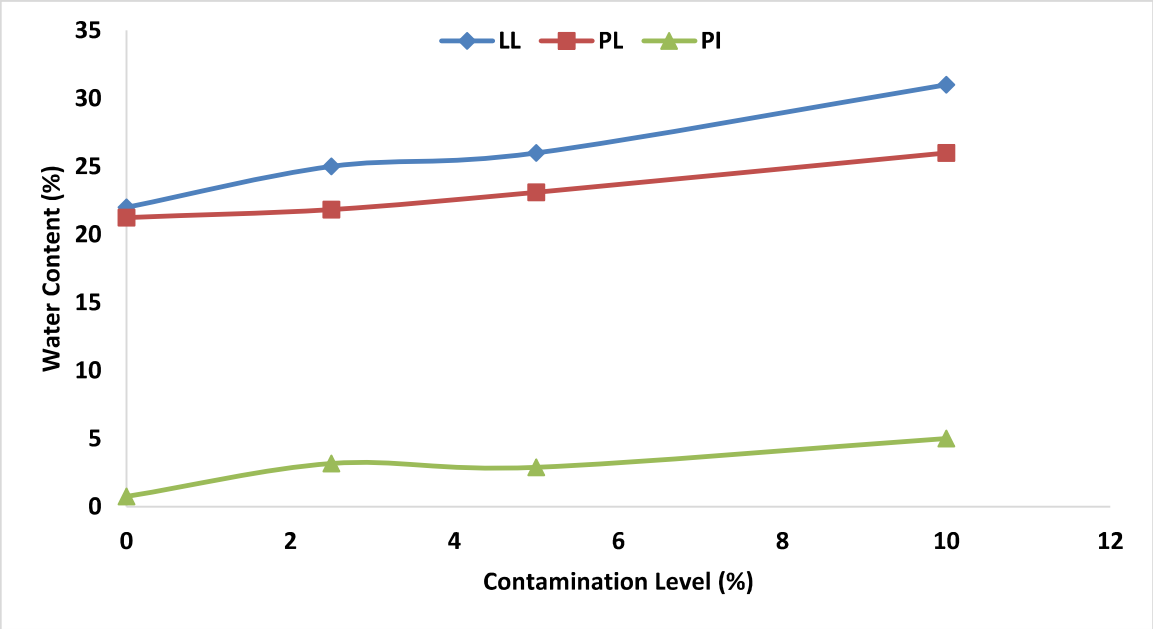


Figure 4.9: Variation of Atterberg Limits of Marl Soil with Diesel Content

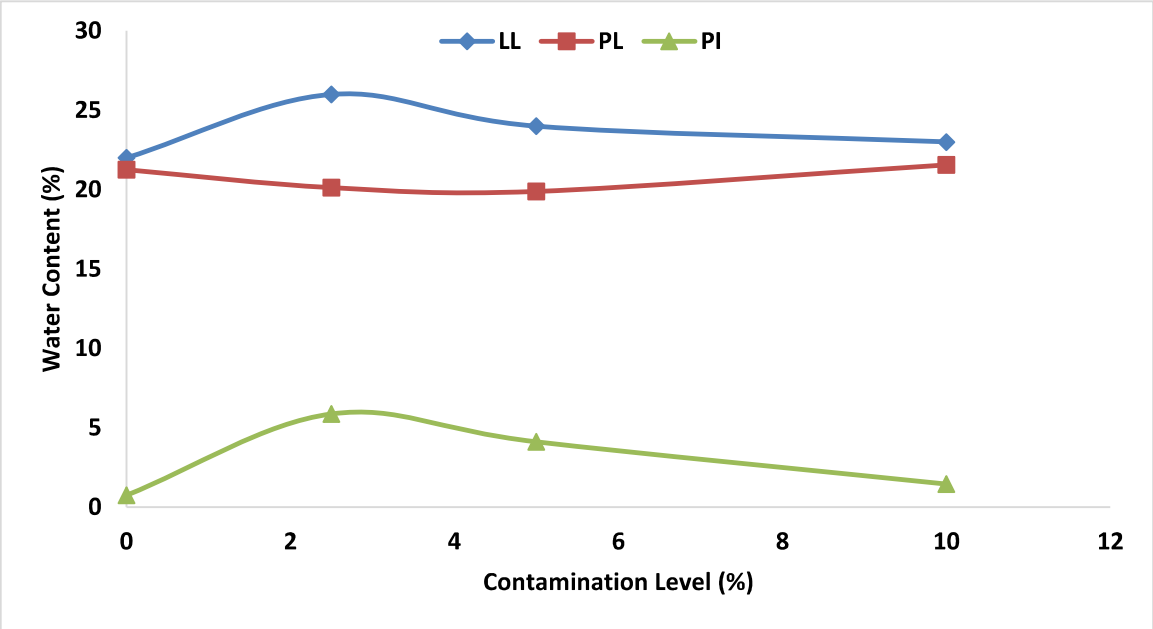


Figure 4.10: Variation of Atterberg Limits of Marl Soil with Crude Oil Content

4.2.4 Maximum Dry Density (Sand)

Figure 4.11 displays the changes in the maximum dry density of the sand (i.e., relative density) after contamination by both diesel and crude oil. As was reported in Section 4.2.2, the particles size of sand has increased, which means that higher porosity and voids are expected. This will lead to a reduction in the maximum dry density, which was indicated through the relative density test, as shown in Figure 4.11. The fact that the dry density of the sand contaminated by crude oil is marginally higher than that obtained with diesel contamination may be attributed to the fact that crude oil is more lubricating than the diesel and thus the soil particles will be more susceptible to rolling and rearranging under load.

One point that was noted during the relative density test is that the crude oil and diesel were coming out of the soil with the high vibration of the table. This behavior explains the marginal change in the density between 2.5% and 10% contamination. As the soil was

initially contaminated, the part of the soil that was replaced by the diesel or crude oil has affected the maximum dry density significantly. However, with increasing the contamination level, the vibration has removed part of the contaminants and the soil particles were allowed to rearrange themselves and thus minimal changes in the density were observed.

4.2.5 Maximum Dry Density and Optimum Moisture Content (Marl)

The characteristics of the compaction for both contamination types (diesel and crude oil) are shown in Figures 4.12 and 4.13, respectively. Figure 4.14 displays the effect of contamination level on the maximum dry density. As shown in Figure 4.14, the crude oil contamination has increased the maximum dry density by 5.8% at 10% contamination level while the diesel has decreased the maximum dry density marginally (about 2.3% reduction at 10% contamination level). Both effects are practically marginal and this behavior is mostly due to the slight difference in density between diesel and crude oil (832 kg/l for diesel and 857.5 kg/l for crude oil).

Figure 4.15 displays the effect of contamination level on the optimum moisture content. The increase in diesel content decreased the moisture content slightly up to 2.5% and, thereafter, increased. However, the crude oil content has decreased the moisture content significantly. Similar behavior for the crude oil contamination was observed by Rehaman et al. (2007). The most probable reason for reduction in OMC is that the crude oil acts as a lubricant agent which means that the soil particles will slide over each other easily and thus achieving MDD at lower moisture content.

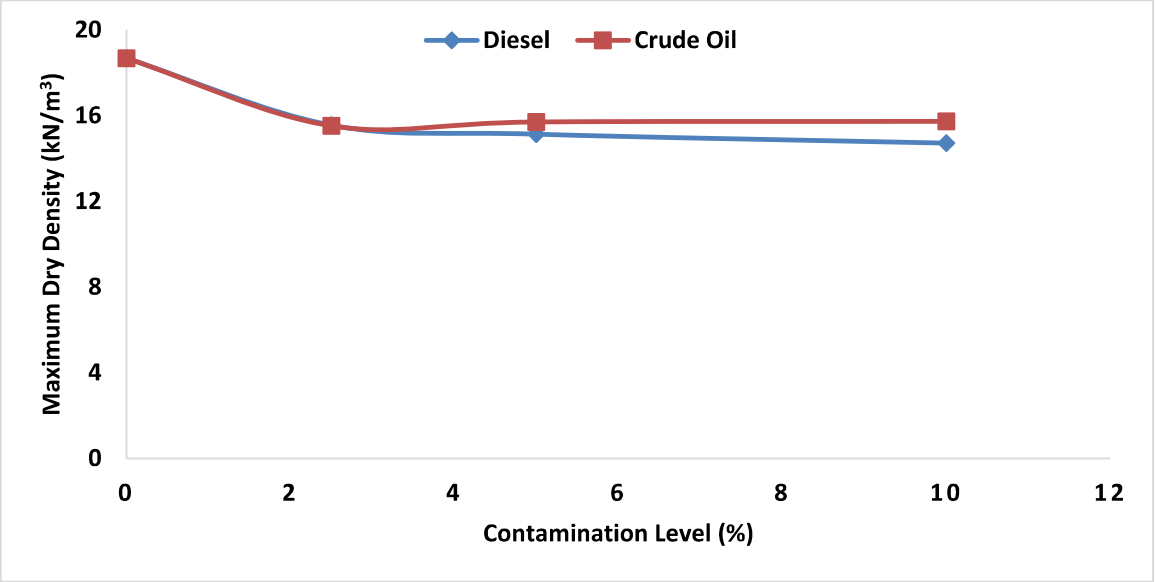


Figure 4.11: Variation of Maximum Dry Density of Sand with Contamination Level

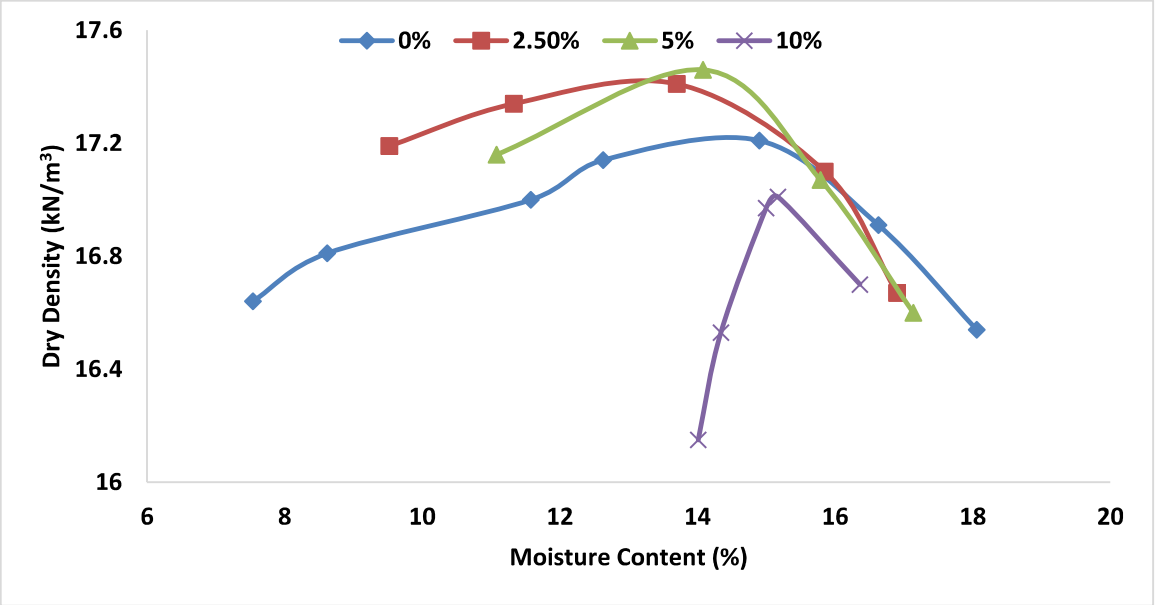


Figure 4.12: Compaction Characteristics of Marl Contaminated by Diesel

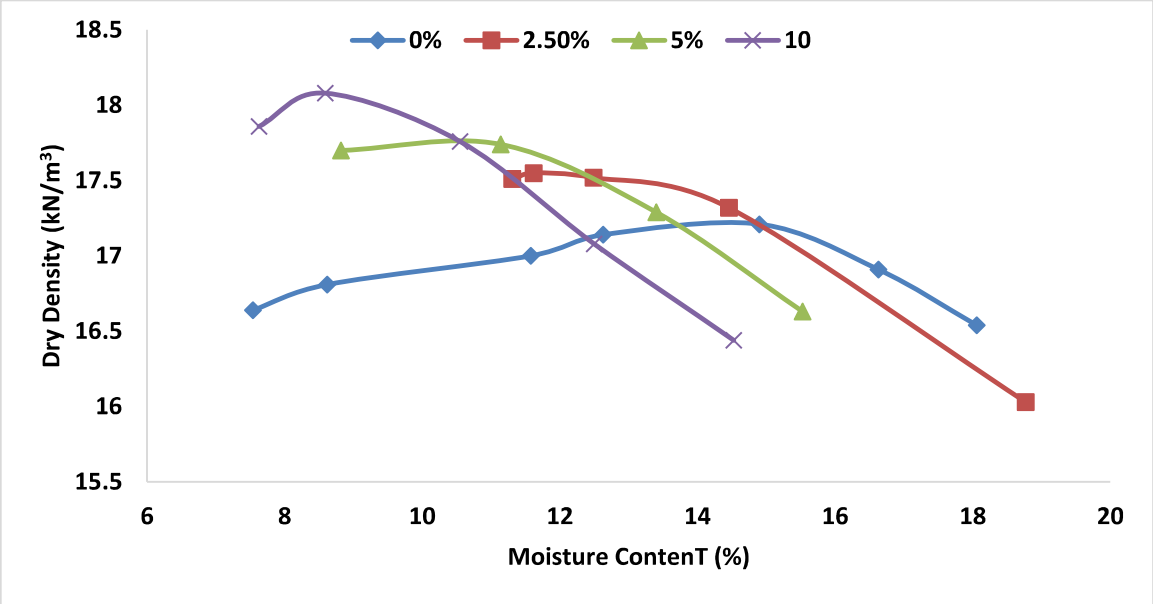


Figure 4.13: Compaction Characteristics of Marl Contaminated by Crude Oil

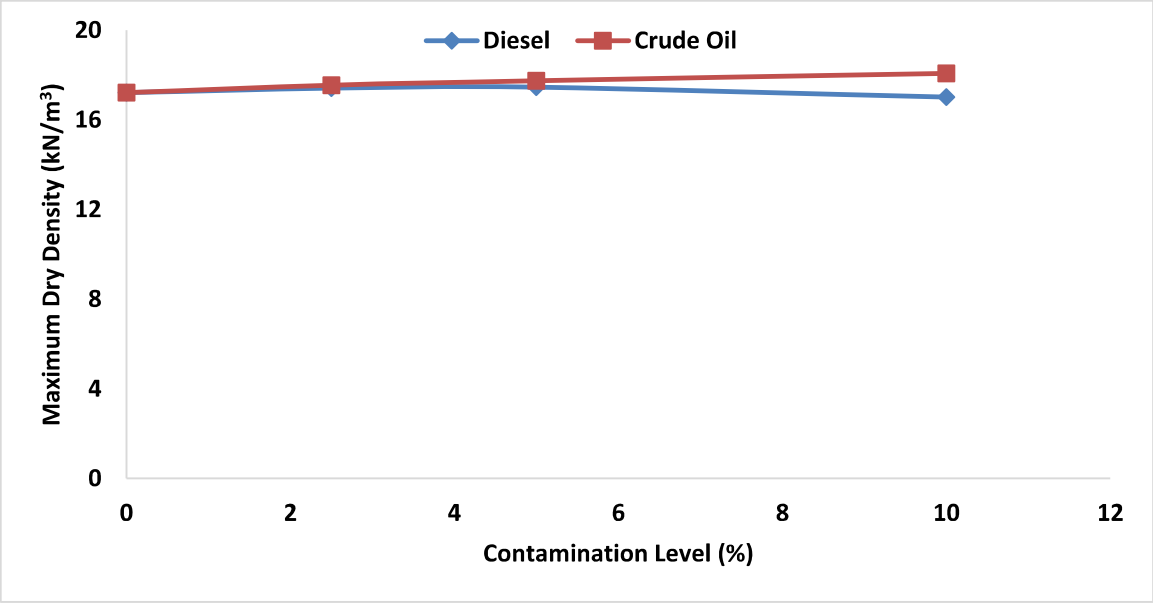


Figure 4.14: Variation of Maximum Dry Density of Marl Contaminated by Diesel and Crude Oil

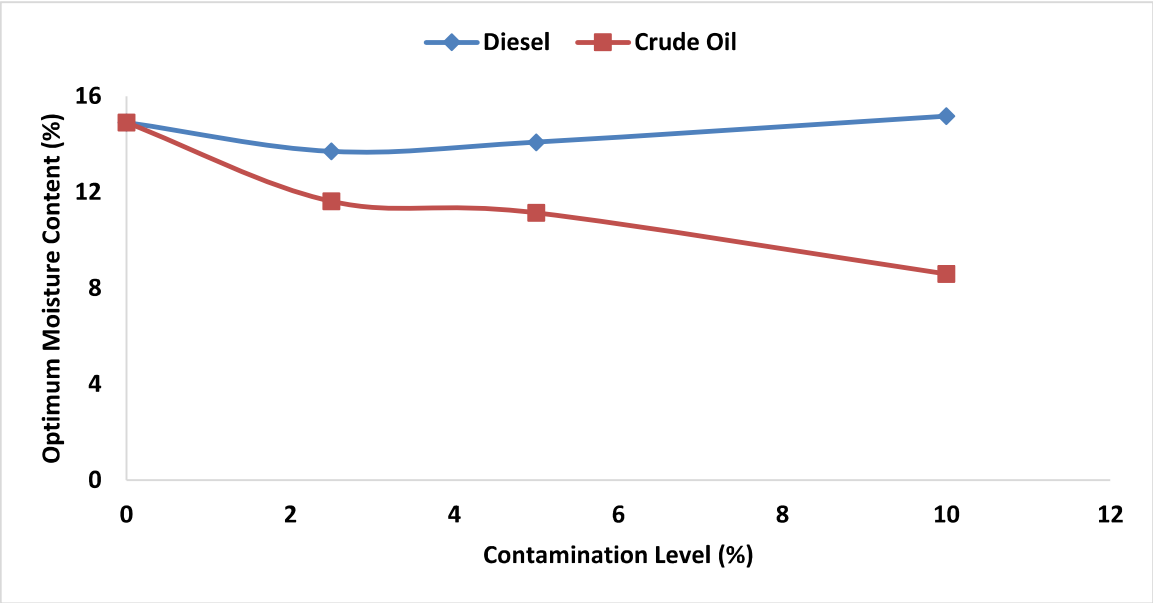


Figure 4.15: Variation of Optimum Moisture Content of Marl Contaminated by Diesel and Crude Oil

4.2.6 Hydraulic Conductivity (Permeability)

Figure 4.16 shows the effect of contamination on the hydraulic conductivity of sand. As shown, the increase in contamination level has led to an increase in the permeability for both diesel and crude oil which may be attributed to the effect of water. The water dissociates the oil-marl bonds due to the high dielectric constant of water (which is nearly 80) compared to that of crude oil (nearly 2) (Mitchell and Soga 2005). With this effect of water, the marl fabric becomes dispersed by increasing the thickness of double layer and thus higher permeability is expected.

In the case of diesel contamination, the permeability has increased up to 2.5% contamination and then started to decrease for the sand. Since the sand particles are not chemically active, as compared with the marls, it is expected that the bond between the

sand particles and oil is weaker than that in the marl. Hence, the water will dissociate the oil and it will not be so that much attracted to the sand particles, meaning the sand particles will slide over each other and rearrange themselves thereby resulting in less permeability. Figure 4.17 shows the effect of contamination on the permeability of marl. As shown in Figure 4.17, increasing the contamination level tends to increase the permeability, which confirms the agglomeration of particles and formation of large bodies, as was discussed in Section 4.2.2.

4.2.7 Unconfined Compressive Strength (UCS) for Marl

The effect of both the diesel and crude oil on the unconfined compressive strength of marl is presented graphically in Figures 4.18, 4.19 and 4.20. As can be seen in these Figures, with increasing the contamination level, UCS decreases gradually. It is to be noted that the effect of crude oil is more than that of the diesel, where a reduction of 18.5% is obtained at 10% contamination by the diesel with 7 days of air-curing as compared to the uncontaminated soil strength, while 63% reduction at 10% contamination with crude oil for the same curing period (7 days).

Figure 4.19 presents the variation of UCS with contamination level at 28 days air-curing. As displayed in this Figure, the UCS of diesel-contaminated marl has increased compared to that of the original soil while in case of crude oil contamination the UCS has decreased with increasing the contamination level. Figure 4.20 shows the UCS values at 90-days air-curing. In the case of diesel contamination, an increase in the UCS value could be observed while a reduction is observed in the case of crude oil. This behavior can be summarized in the following two points (Li et al, 2004):

- The losses due to volatilization in the diesel are higher than that in the crude oil (20% for the diesel and 3% for the crude oil by weight). This means that with the diesel being lost, the water and soil particles will have more area to interact and forming strong bonds and, thus, increasing the strength of the soil. On the other hand, the volatilization (or evaporation) losses in crude oil are expected to be low and thus the water will have lesser area to interact with soil particles and, therefore, lower strength due to the weaker bonds is expected. Therefore, the strength of diesel-contaminated soil is higher than that of crude oil-contaminated soil.
- Both Figures 4.21 and 4.22 present the effect of curing period on the UCS of marl. As shown in Figure 4.21, UCS of the marl in the case of diesel contamination level is increasing with increasing the curing period due to the loss of volatilization as discussed in the previous point. It is to be noted that the higher strength is achieved in case of 5% contamination level. Figure 4.22 presents the effect of curing period on the UCS values and as can be seen, increasing the curing period tends to increase the UCS for all level of contamination.

Therefore, if the soil is allowed to be air-dried for about 7 days (as was done in this research), the diesel and crude oil will have these volatilization losses and thus we can treat the soil, it should be noted that these losses will not stop, but they will be as low as possible with time.

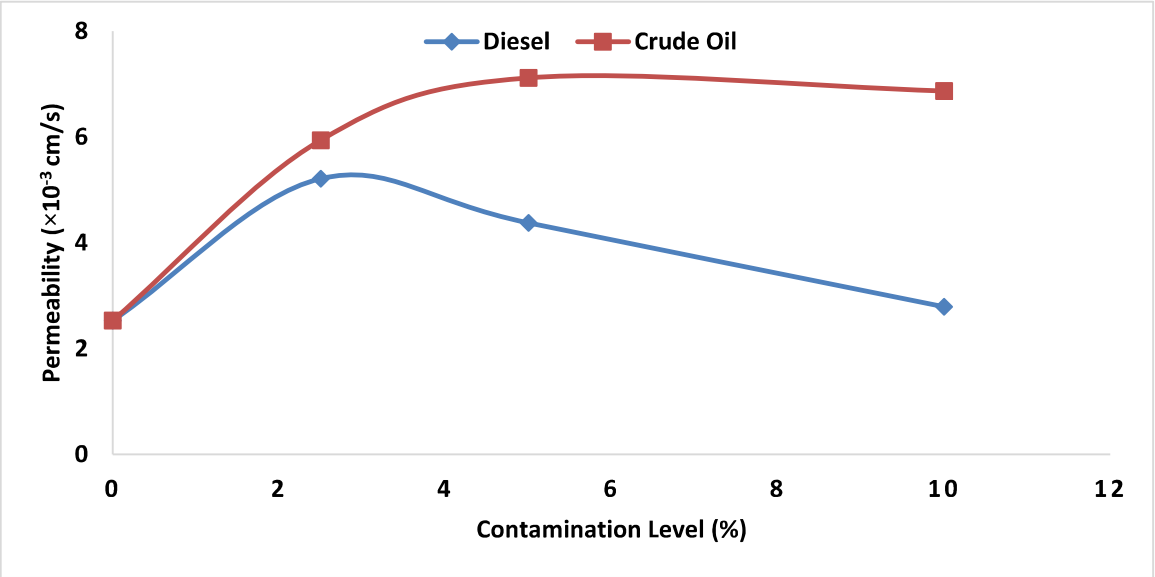


Figure 4.16: Variation of Hydraulic Conductivity of Sand with Contamination Level

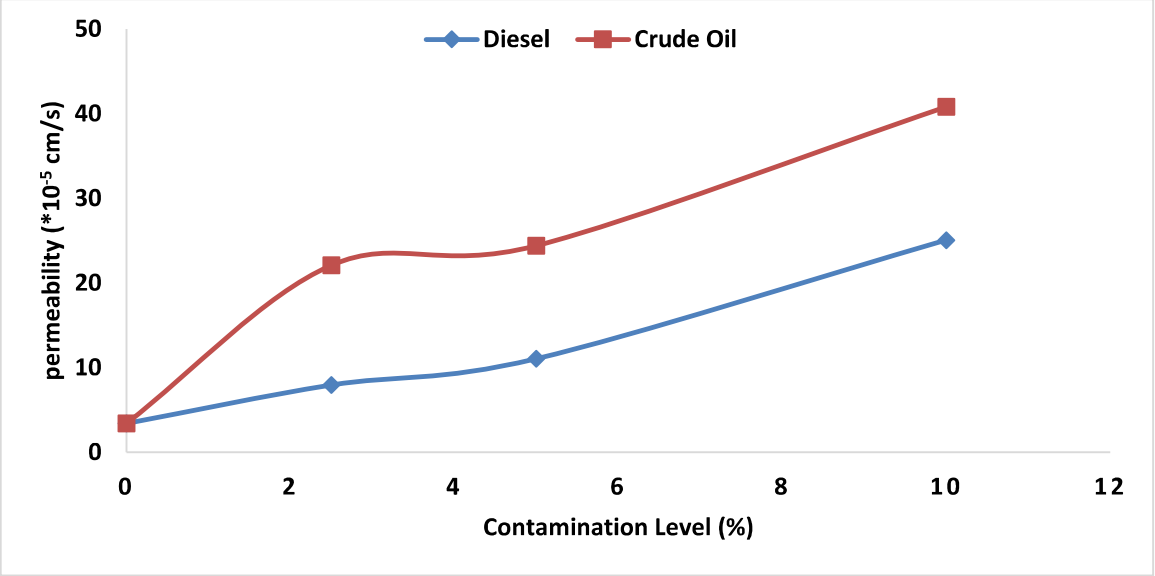


Figure 4.17: Variation of Hydraulic Conductivity of Marl with Contamination Level

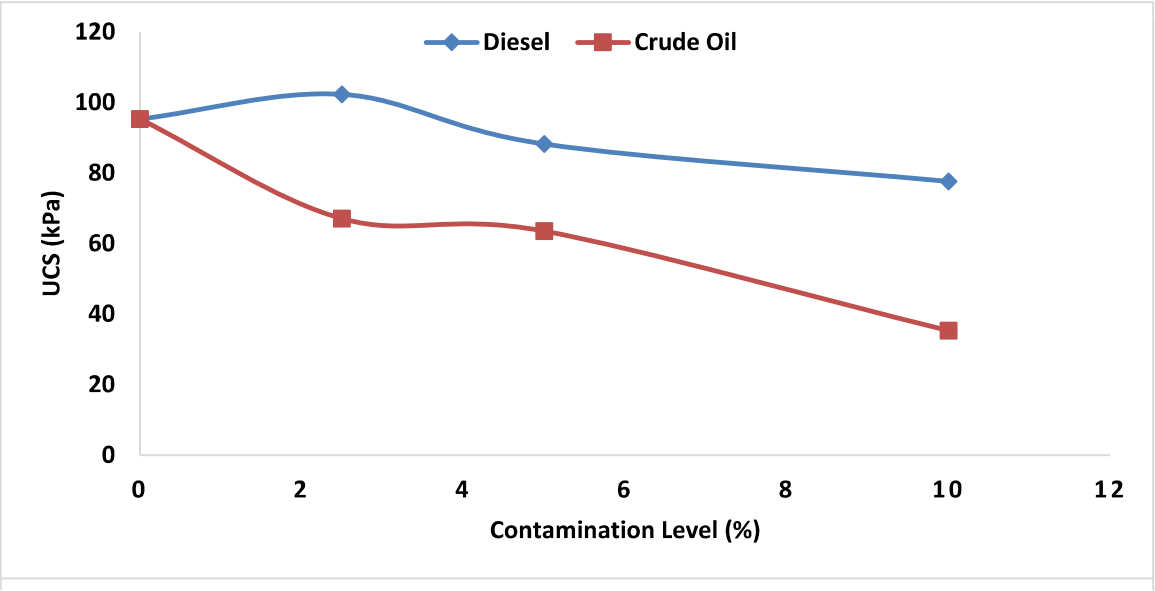


Figure 4.18: Variation of UCS of Marl with Contamination Level (7 Days Curing)

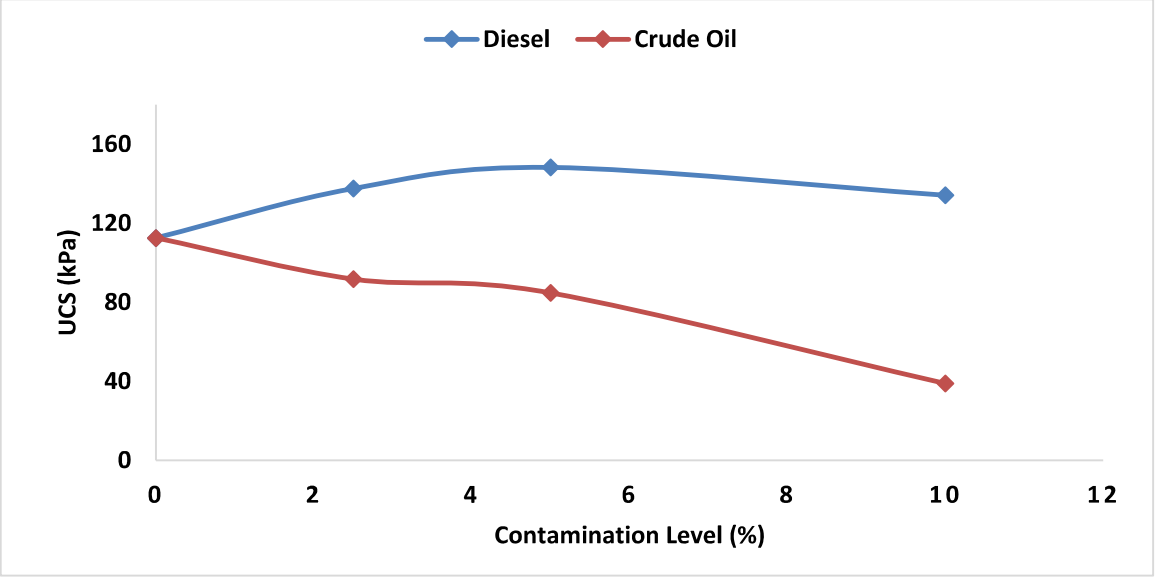


Figure 4.19: Variation of UCS of Marl with Contamination Level (28 Days Curing)

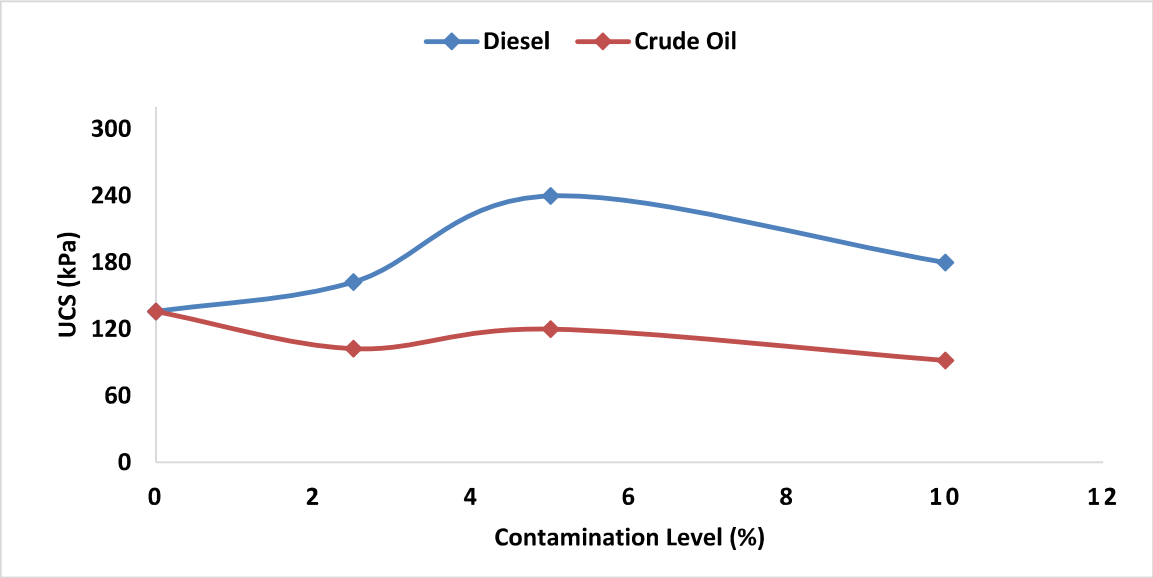


Figure 4.20: Variation of UCS of Marl with Contamination Level (90 Days Curing)

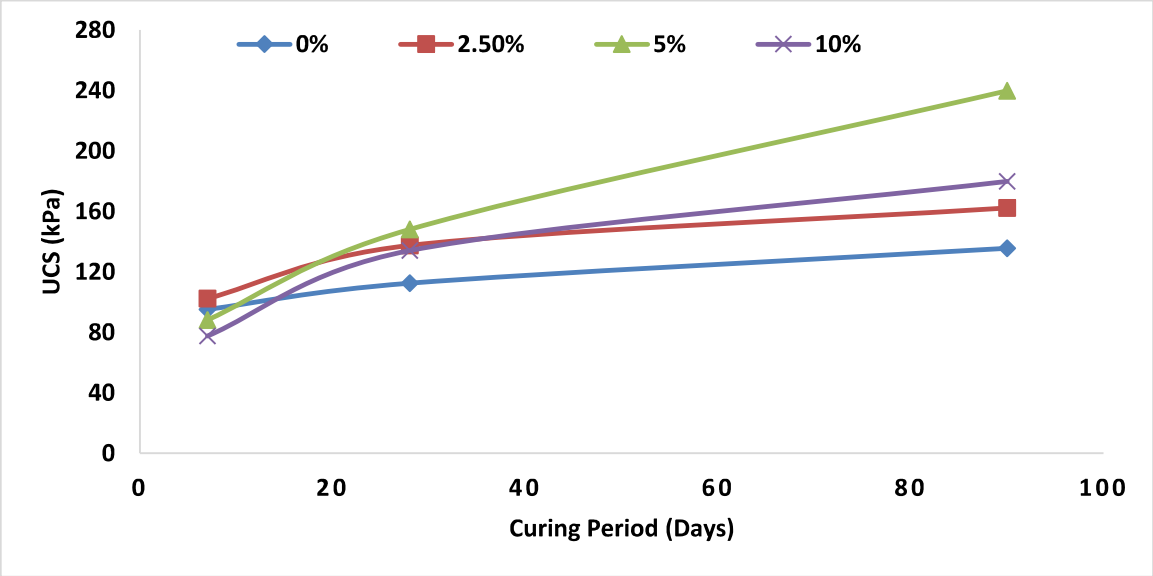


Figure 4.21: Variation of UCS with Curing Periods for Marl Contaminated with Diesel

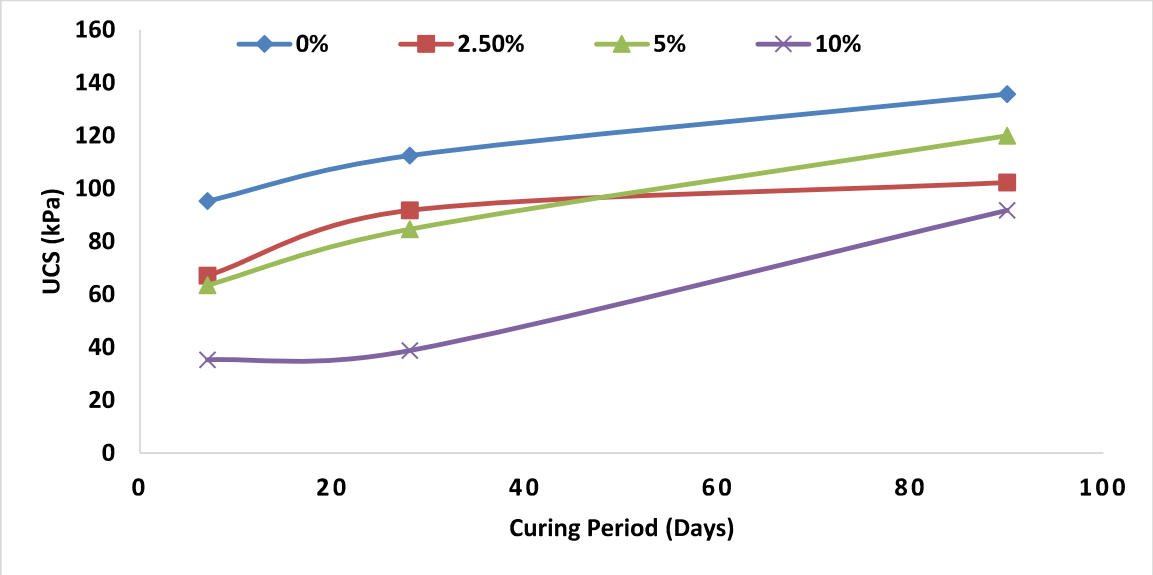


Figure 4.22: Variation of UCS with Curing Periods for Marl Contaminated with Crude Oil

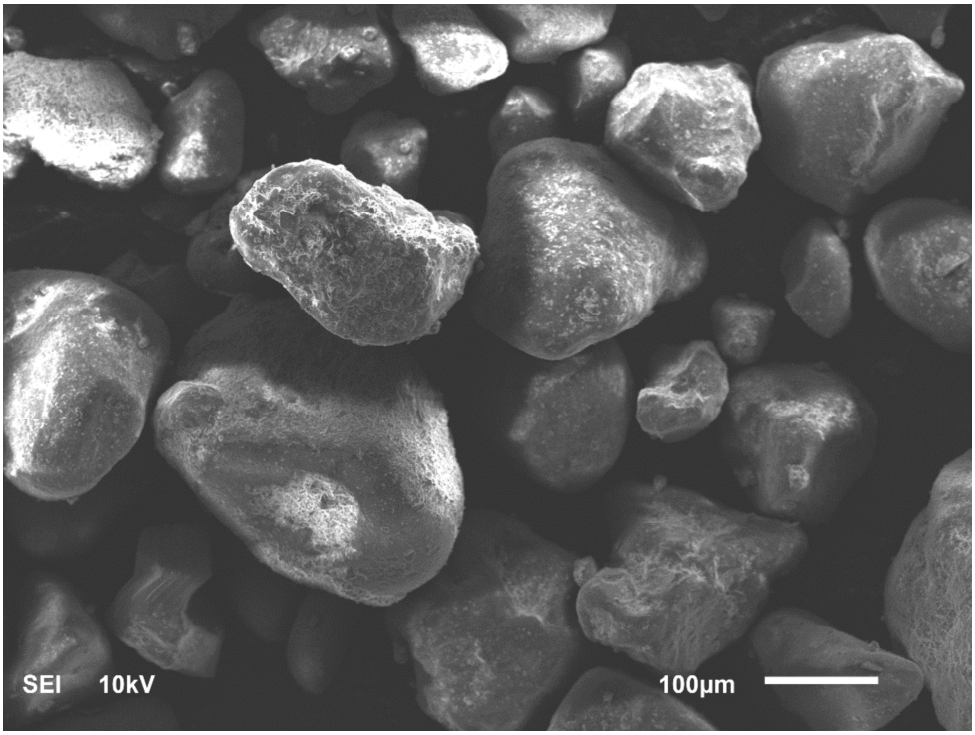
4.2.8 SEM/EDS Analysis

SEM analysis was carried out for the 10% contamination level (diesel and crude oil) for both sand and marl soils. Figures 4.23 and 4.24 show the effect of the diesel and crude oil on the sand fabric. As shown in Figure 4.23, the sand particles are coated with hydrocarbon products as was confirmed with the EDS analysis (Table 4.3). Figure 4.24 shows the coating of soil particles by the crude oil and the dispersed fabric. To see how the elemental compositions is different from that of the uncontaminated sand, Table 4.3 displays numerically the results of EDS analysis showing the difference between the uncontaminated and both 10% diesel contaminated and 10% crude oil contamination in the weight of the basic elements. As shown in Table 4.3, a slight increase in the weight of carbon is observed in the case of 10% diesel contamination while a large increase is

noted in the case of 10% crude oil contamination. This increase in carbon content is an indicator of the presence of hydrocarbons which is larger in crude oil in this study. Another element that has experienced a large increase compared with the uncontaminated sand is the calcium, which could be an indication of the presence of calcium in both crude oil and diesel. Silica content has decreased almost by 95% in the case of 10% diesel contamination and by 97% in case of 10% crude oil contamination as compared to uncontaminated sand. This large reduction in silica is attributed to the fact that the contaminants are replacing part of the soil when mixing.

Referring to Figures 4.25 and 4.26, the presence of diesel and crude oil on the marl particles is observed. First, the marl particles were agglomerated due to the lower dielectric constant of both diesel and crude oil. Second, some hydrocarbons coating is observed on the surface of marl particles, as was noted in Figures 4.23 and 4.24 for the case of sand. Table 4.4 shows the EDS analysis for marl soil. As shown in Table 4.4, the amount of carbon is higher in the case of diesel (about 125% higher) and higher in the case of crude oil (about 170% higher) compared to the uncontaminated marl, which is attributed to the presence of hydrocarbons as in the sand case. A slight reduction is observed in the case of both Ca and Mg (two major components of the dolomite), which is attributed to the replacement of dolomite by the contaminants in both diesel and crude oil.

a)



b)

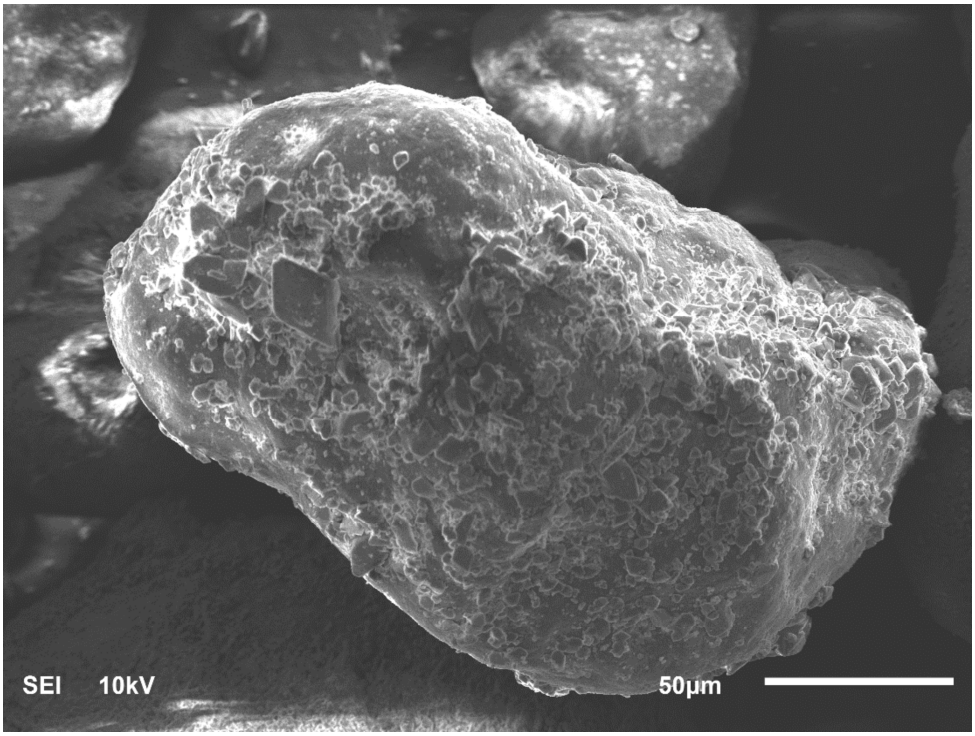


Figure 4.23: SEM Images of Sand Contaminated by 10% Diesel at Magnification of: (a) 100 µm (b) 50 µm

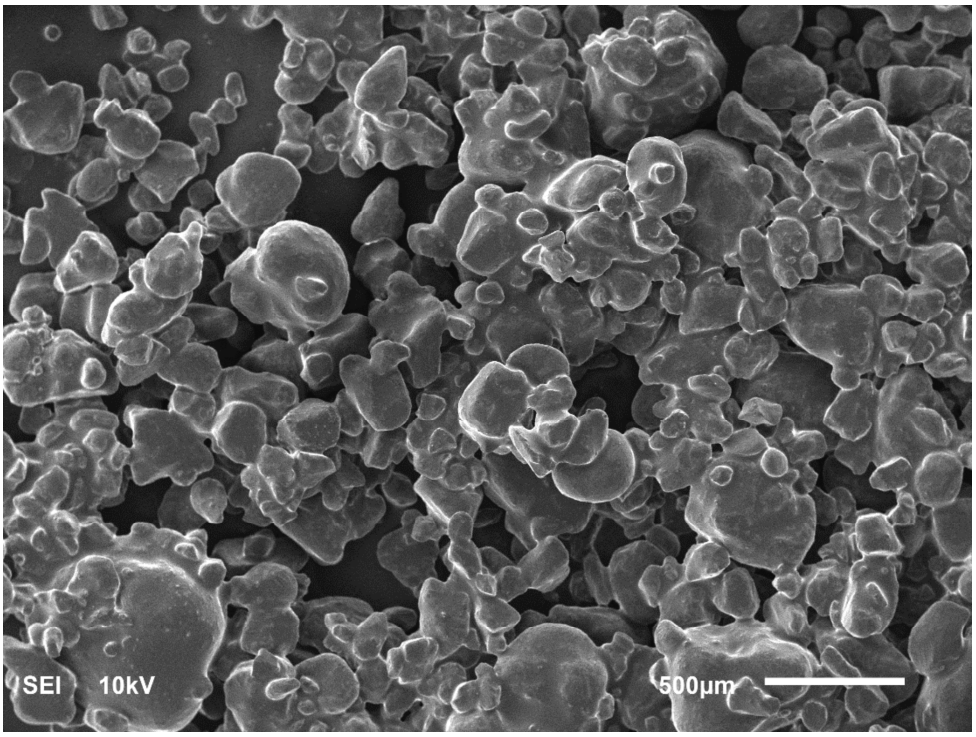
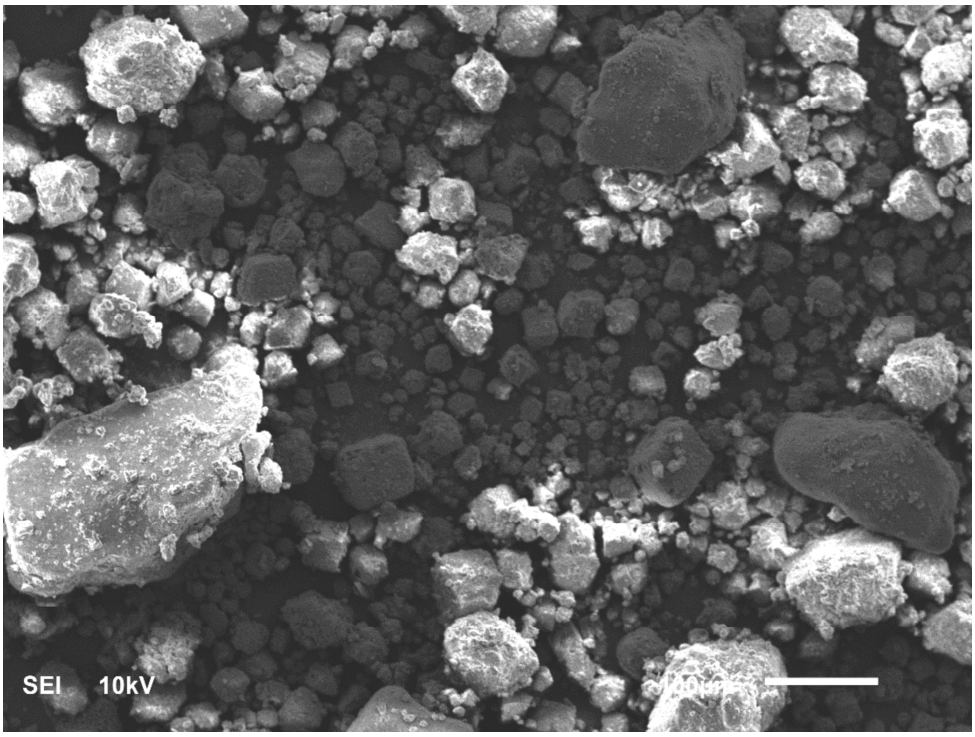


Figure 4.24: SEM Images of Sand Contaminated by 10% Crude Oil at Magnification of: (500 µm)

Table 4.3: Summary of EDS Analysis Results for Contaminated Sand (Weight, %)

Elements	Uncontaminated	10% Diesel	10% Crude Oil
C	22.62	28.59	44.01
O	44.05	42.05	33.08
Si	30.76	1.63	0.94
Ca	2.57	27.73	21.97
Total	100	100	100

a)



b)

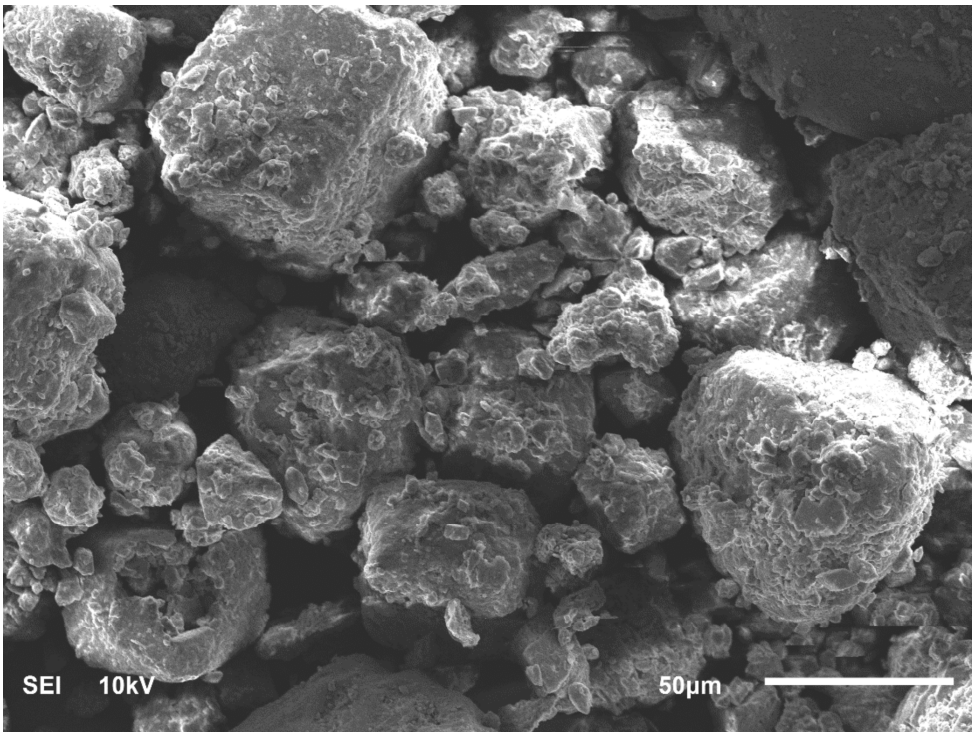
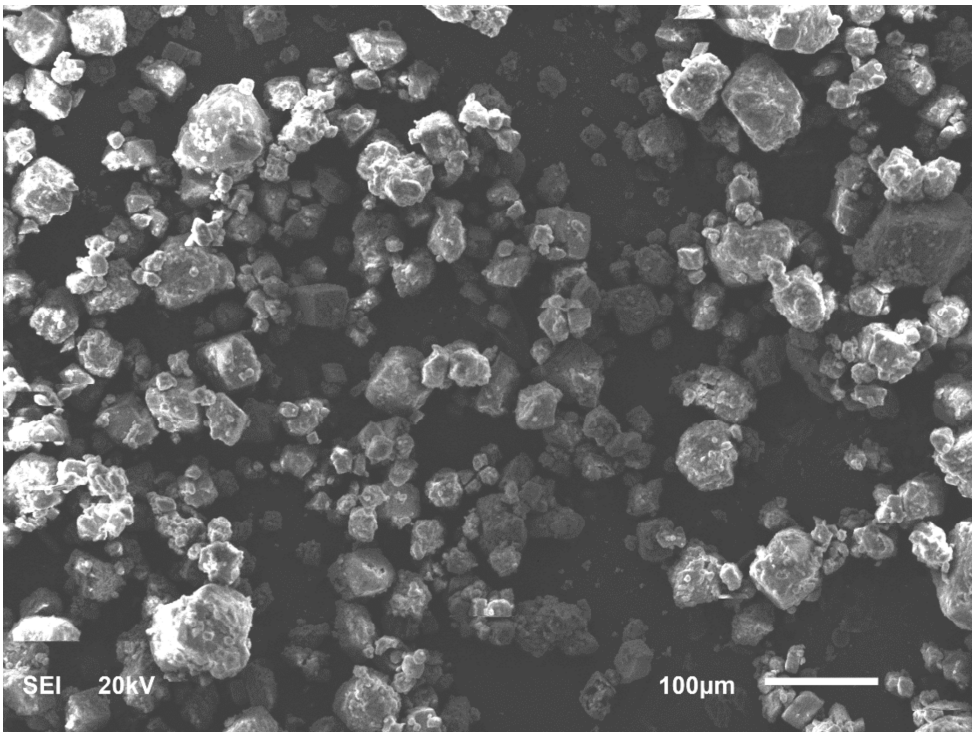


Figure 4.25: SEM Images of Marl Contaminated by 10% Diesel at Magnification of: (a) 100 µm (b) 50 µm

a)



b)

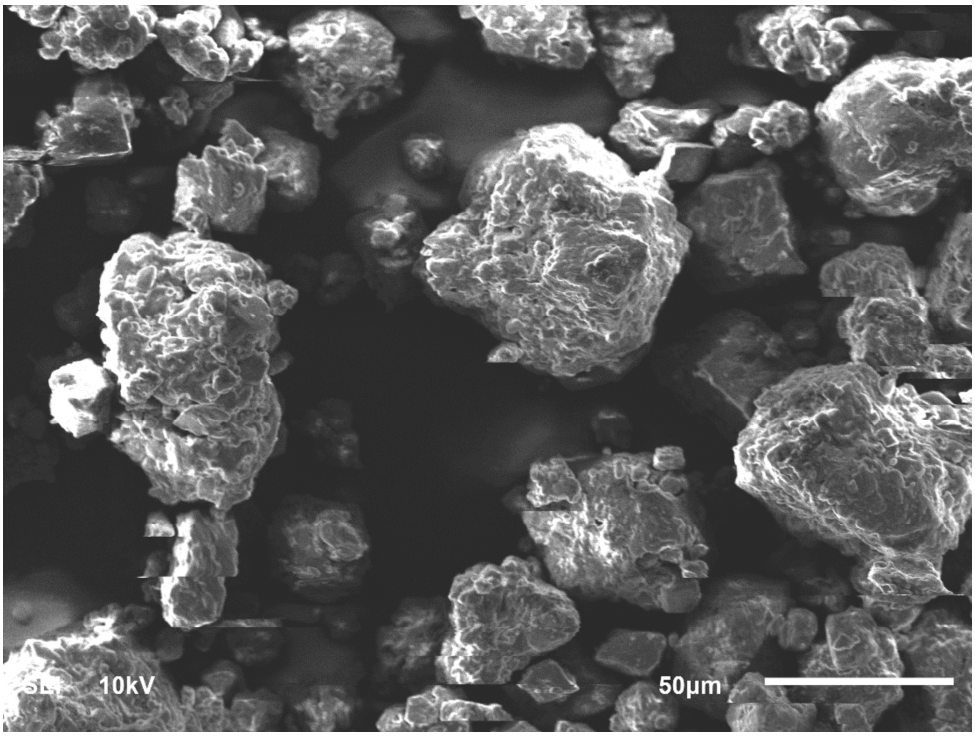


Figure 4.26: SEM Images of Marl Contaminated by 10% Crude Oil at Magnification of: (a) 100 µm (b) 50 µm

Table 4.4: Summary of EDS Analysis Results for Contaminated Marl (Weight, %)

Elements	Uncontaminated	10% Diesel	10% Crude Oil
C	17.38	39.11	46.98
O	53.77	37.60	24.92
Si	4.14	5.65	6.61
Ca	16.18	11.67	13.80
Mg	7.27	4.60	5.81
Total	98.74	98.63	98.12

4.2.9 TPH Analysis

As the soil was contaminated by the diesel and crude oil, the TPH values were determined for the contaminated soil in order to determine whether this contamination is considered as high, medium or low. The results obtained for the TPH analysis are numerically presented in Table 4.5. The data in Table 4.5 indicate that the TPH content is increasing gradually with the contamination level as expected. TPH content obtained in the case of diesel are always higher than that for crude oil due to the fact that diesel is considered as a purified material and thus the TPH content would be higher than that for the crude oil which is not pure and might contain impurities that reduce the TPH content (Communication with RI Officials).

Table 4.5: TPH Analysis for Both Contaminated Sand and Marl (values in ppm)

	Contamination Level (%)	Sand	Marl
Uncontaminated	0	21.3	5.8
Diesel	2.5	13,255	15,425
	5	27,155	31,527
	10	54,010	60,924
Crude Oil	2.5	6,218	5,422
	5	11,925	10,251
	10	23,516	20,906

4.3 Stabilization/Solidification Treatment

As mentioned in Section 2.5, each of the contaminated soil was mixed with three different types of stabilizers at different proportions, as indicated in Table 3.1. The stabilized mixtures were tested to determine the maximum dry density and optimum moisture content in order to use these parameters for preparation of UCS samples.

4.3.1 Compaction Characteristics of Stabilized Contaminated Sand

The compaction characteristics of the contaminated sand are numerically presented in Table 4.6. and graphically in Figures 4.27 and 4.28 for diesel and Figures 4.29 and 4.30 for crude oil. For the diesel contamination of sand, the data in Figure 4.27 indicate that the maximum dry density has increased by 19% at 7.5% OPC as compared to the contaminated soil. The increase in maximum dry density (MDD) is mostly due to the difference in specific gravity since the cement has a specific gravity of about 3.15 which is higher than that of the soil (Al-Homidy 2013). It should be noted that the maximum MDD among all stabilizers was achieved by the 2.5% OPC + 40% LSP, which may be attributed to the fineness of LSP that tends to fill the voids among the sand particles thereby producing very dense matrix. Such a hypothesis is verified by the fact that as the

LSP content increases, the MDD tends to increase (see Figure 4.27 and Table 4.6). Further, LSP is known for its ability to pack cement granular skeleton and thus decrease the volume of pores which increases the density (Bonavetti, 2003).

For the CKD case, Figure 4.27 shows that increasing the CKD content (with the addition of 2.5% OPC) is increasing the MDD of the soil. Further, the density achieved in the case of CKD-stabilized mixtures is almost similar to that achieved in the case of OPC stablization due to the similarities of cement and CKD.

In the case of OMC, as shown in Figure 4.28, the OMC decrease in the presence of OPC and CKD while it increases with the increase in the LSP content. The reason for the increase in the OMC with the increase in the LSP content is ascribed to the presence of the calcite which is a crystalline mineral that usually has prism micro-structure which means more surface area and thus requires more water (Mitchell and Soga 2005). This issue will be discussed later in Section 4.3.6. The reduction in the OMC for both cement and CKD may have resulted from the clogging of voids by the small particles of such materials.

Similar behavior could be observed for crude oil contamination. As shown in Figure 4.30, the OMC is marginally increasing with increasing the cement content. This behavior could be ascribed to the fact that the crude oil is preventing the cement from interacting with the soil, which means that the cement will require more water as compared to the diesel.

Table 4.6: Summary of Compaction Characteristics for Contaminated Sand

Contamination Level	2.5%				5%				10%			
Contaminant Type	Diesel		Crude Oil		Diesel		Crude Oil		Diesel		Crude Oil	
Stabilizer Type and Dosage	MDD	OMC	MDD	OMC	MDD	OMC	MDD	OMC	MDD	OMC	MDD	OMC
Without Stabilizer	**15.56**	**-**	**15.52**	**-**	**15.13**	**-**	**15.71**	**-**	**14.71**	**-**	**15.73**	**-**
2.5% OPC	18.26	9.30	18.22	10.56	18.21	9.54	18.48	8.28	17.88	10.33	18.7	3.11
5% OPC	18.36	8.79	18.5	10.45	18.23	9.01	18.6	9.19	17.99	9.39	18.89	5.67
7.5% OPC	18.51	8.96	18.57	13.81	18.45	9.12	18.93	12.42	18.09	9.05	19.04	6.29
2.5% OPC + 10% LSP	19.15	10.22	19.28	10	19.01	10.50	19.55	9.56	19.1	11.05	19.53	8.17
2.5% OPC + 20% LSP	19.96	11.64	20.01	10.11	19.89	11.85	20.46	8.02	18.97	12.32	19.76	8.39
2.5% OPC + 40% LSP	20.31	11.58	20.33	10.62	19.92	11.93	20.55	9.6	19.74	12.82	19.76	10.55
2.5% OPC + 5% CKD	18.01	10.55	17.01	5.78	17.65	10.20	17.22	6.01	17.25	6.12	17.34	8.36
2.5% OPC + 10% CKD	19.02	11.21	17.59	7.86	18.88	10.46	17.72	8.1	18.2	7.39	18.78	10.01
2.5% OPC + 20% CKD	19.25	8.69	18.1	5.63	18.95	8.39	18.25	5.87	18.52	7.6	18.96	6.93

MDD: in kN/m^3

OMC: in %

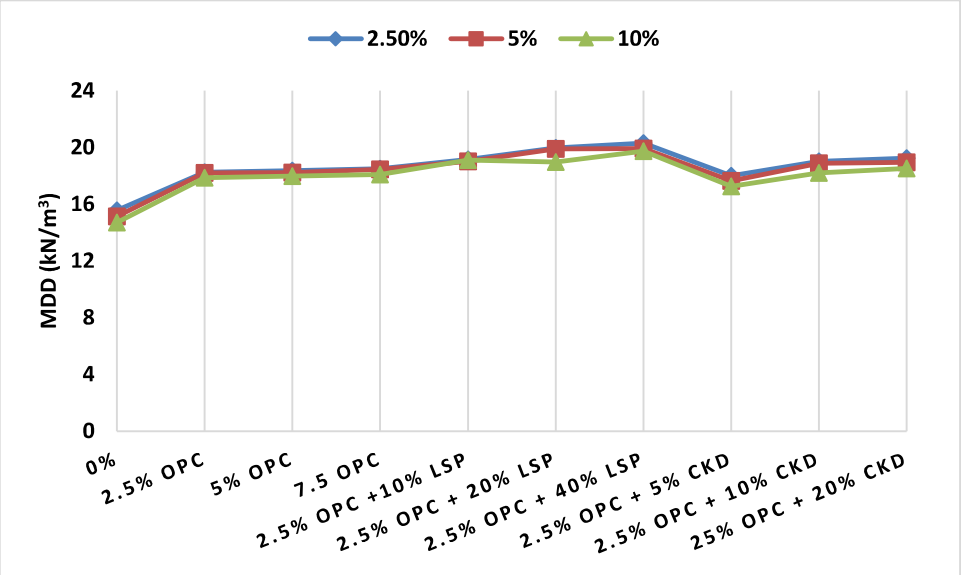


Figure 4.27: Variation of MDD of Sand with Different Stabilizers at Three Levels of Contamination by Diesel

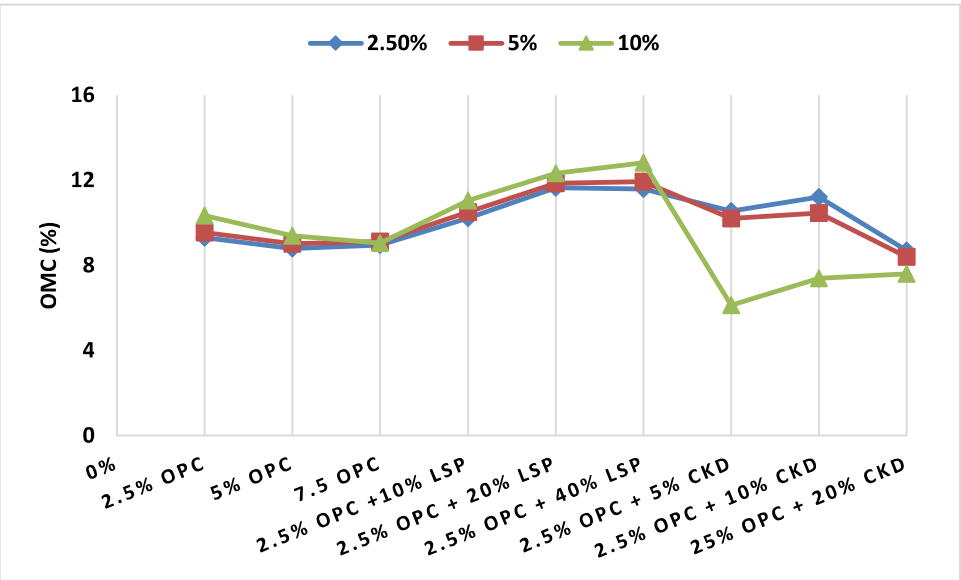


Figure 4.28: Variation of OMC of Sand with Different Stabilizers at Three Levels of Contamination by Diesel

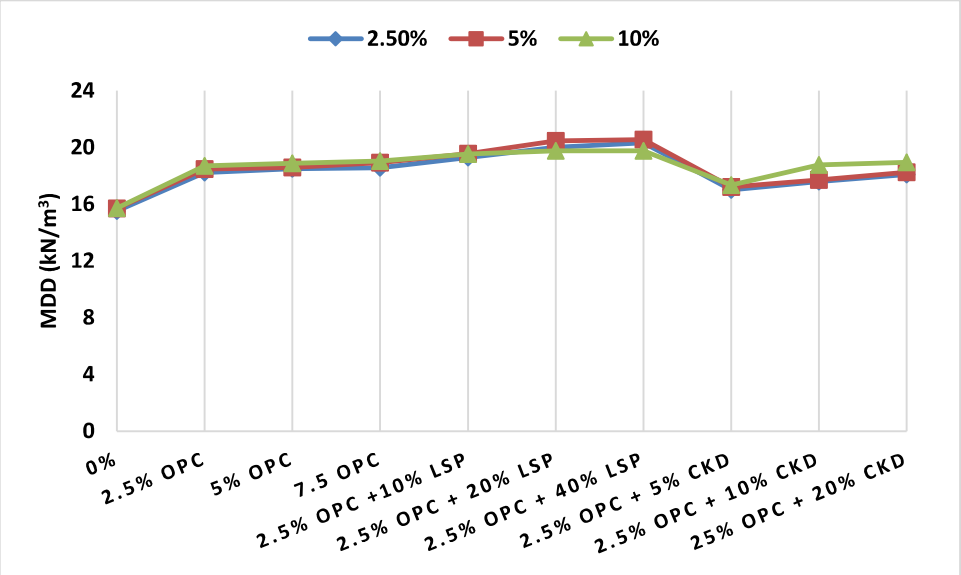


Figure 4.29: Variation of MDD of Sand with Different Stabilizers at Three Levels of Contamination by Crude Oil

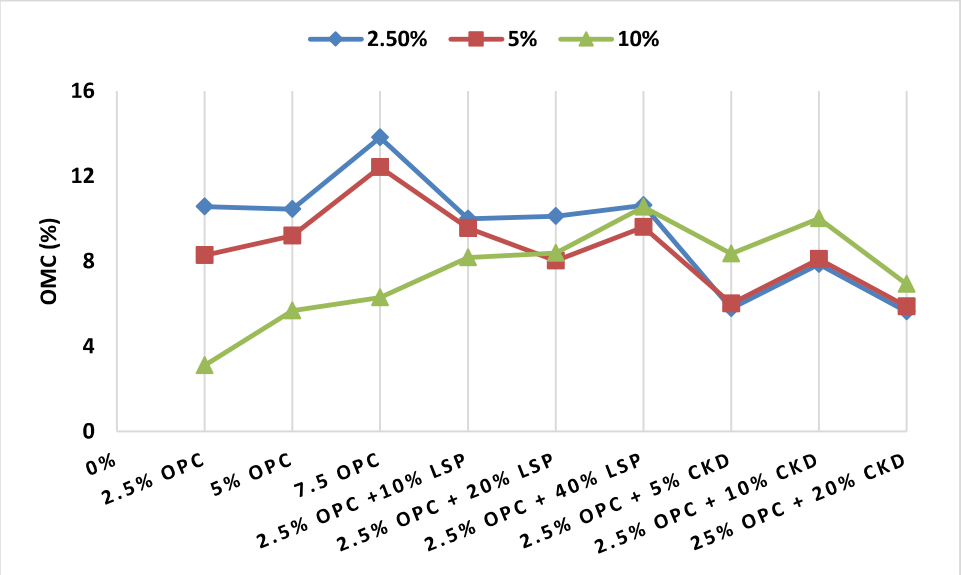


Figure 4.30: Variation of OMC of Sand with Different Stabilizers at Three Levels of Contamination by Crude Oil

4.3.2 Compaction Characteristics of Stabilized Contaminated Marl

The compaction characteristics of the contaminated marl are numerically presented in Table 4.7 and graphically in Figures 4.31 and 4.32 for diesel and Figures 4.33 and 4.34 for crude oil. The same behavior that was observed in the case of sand treatment could be observed here. A general note is that in the case of MDD (as seen in Figures 4.31 and 4.33) that only marginal changes could be observed for all stabilizers (no reduction in MDD as was noted for sand), which may be attributed to the fine particle sizes of the marl which could be acting as a filler to the large voids.

It is to be noted that there is no large variation in the OMC of all mixes (see Figure 4.34). This may be due to the fact that marl particles are chemically active and thus they affect and attract the water even in the presence of the stabilizers.

Table 4.7: Summary of Compaction Characteristics for Contaminated Marl

Contamination Level	2.5%				5%				10%			
Contaminant Type	Diesel		Crude Oil		Diesel		Crude Oil		Diesel		Crude Oil	
Stabilizer Type and Dosage	MDD	OMC	MDD	OMC	MDD	OMC	MDD	OMC	MDD	OMC	MDD	OMC
Without Stabilizer	**17.41**	**13.7**	**17.55**	**11.62**	**17.46**	**14.08**	**17.74**	**11.14**	**17.01**	**15.17**	**18.08**	**8.59**
2.5% OPC	17.44	13.65	17.21	16.30	17.46	14.65	17.3	15.98	17.1	15.39	17.43	16.07
5% OPC	17.46	12.18	17.25	16.22	17.59	12.57	17.35	15.20	17.28	12.94	17.54	13.06
7.5% OPC	17.96	12.53	17.3	16.41	18.08	12.61	17.42	16.22	17.53	12.9	17.62	16.19
2.5% OPC + 10% LSP	17.56	16.50	17.18	16.20	17.75	17.01	17.4	15.21	17.29	17.55	17.63	15.24
2.5% OPC + 20% LSP	17.69	17.20	17.25	16.30	17.78	17.53	17.5	15.19	17.31	17.99	17.72	14.76
2.5% OPC + 40% LSP	17.8	11.59	17.3	16.45	17.97	11.87	17.52	15.89	17.9	11.67	17.83	14.22
2.5% OPC + 5% CKD	17.1	15.30	16.89	16.39	17.34	14.33	16.83	16.47	16.5	19.53	16.7	14.41
2.5% OPC + 10% CKD	17.3	16.55	16.89	16.66	17.44	15.18	17.09	16.40	16.86	20.65	17.17	14.22
2.5% OPC + 20% CKD	17.32	15.31	17.05	16.40	17.49	14.60	17.2	16.19	16.94	18.66	17.52	16.35

MDD: in kN/m^3

OMC: in %

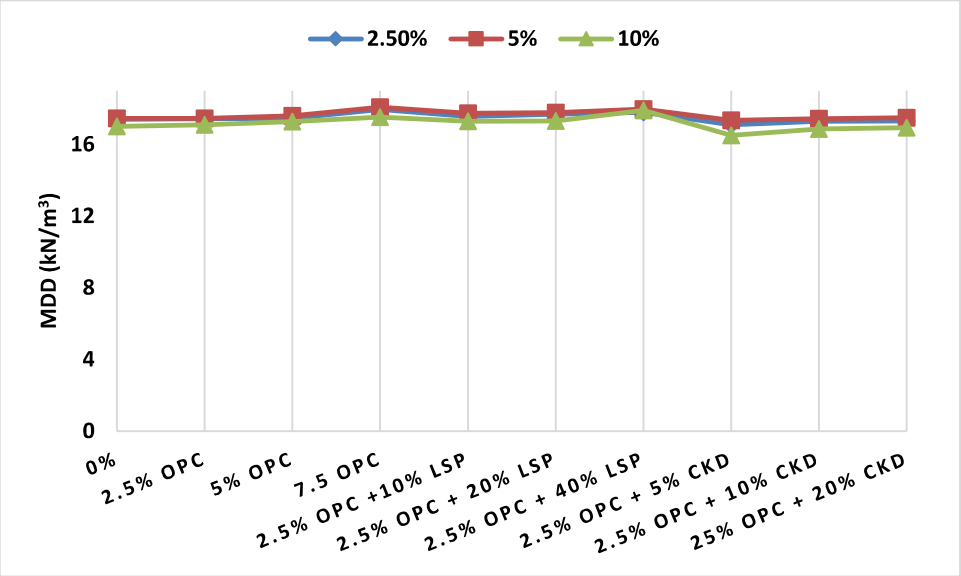


Figure 4.31: Variation of MDD of Marl with Different Stabilizers at Three Levels of Contamination by Diesel (Marl)

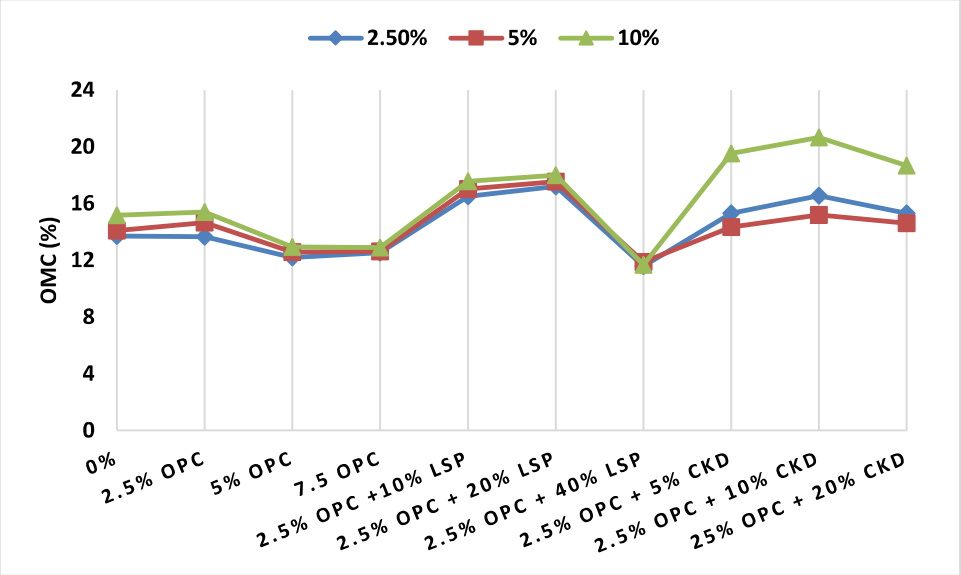


Figure 4.32: Variation of OMC of Marl with Different Stabilizers at Three Levels of Contamination by Diesel (Marl)

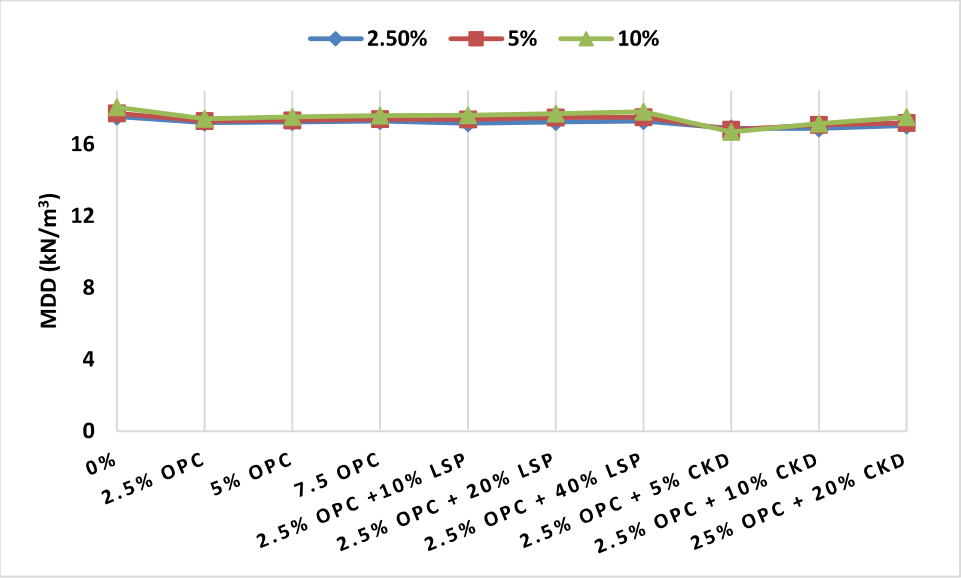


Figure 4.33: Variation of MDD of Marl with Different Stabilizers at Three Levels of Contamination by Crude Oil (Marl)

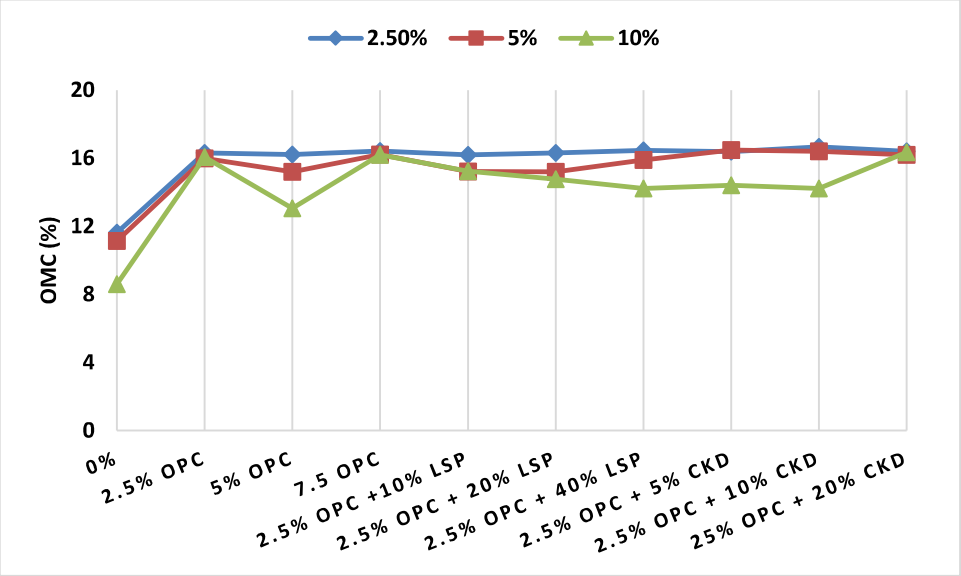


Figure 4.34: Variation of OMC of the Marl with the Different Stabilizers at Three Levels of Contamination by Crude Oil (Marl)

4.3.3 Unconfined Compressive Strength

As discussed in Section 4.3, UCS is one of the parameters that are considered in order to evaluate the effectiveness of S/S treatment. It is be reported that the USEPA has specified a UCS value of 340 kPa to consider the stabilized soil as an “acceptable” criterion for use in engineering applications. Therefore, this criterion will evaluated for all the mixtures used in this investigation.

Figures 4.35 and 4.36 show graphically the UCS values obtained for the stabilized sand after being sealed-cured for seven days. Comparing these results with the USEPA strength requirements (UCS > 340 kPa) indicates that the OPC stabilization displayed good results in the case of diesel contamination except for 2.5% mixture. While for the crude oil contamination, both 2.5% and 5% mixtures have failed to pass the USEPA requirement. On the other hand, all the samples that were stabilized by LSP have passed the USEPA requirement for both diesel and crude oil contamination. In the case of CKD stabilization, none of the contaminated samples that were treated with CKD have passed the requirements. Such a behavior could be ascribed to the fact that the reaction was slowed down in the presence of petroleum products which have affected the development of strength (Akinwumi et al, 2016).

The variation of UCS at 7-day curing for the contaminated marl is shown graphically in Figures 4.37 and 4.38. For the diesel contamination, all the stabilized mixtures have passed the USEPA requirement, as shown in Figure 4.37. For the crude oil contamination (see Figure 4.38), all the mixtures have passed the USEPA requirement, except for the 5% CKD and 20% CKD for 5 and 10% contamination. These relatively better results of

CKD-marl mixtures (than the sand) may be attributed to the reactivity of CKD with marl soil as compared with sand.

The results of UCS at different curing periods (7, 28 and 90 days) are presented numerically in Tables 4.8, 4.9 and 4.10 for sand, and in Tables 4.11, 4.12 and 4.13 for marl. As can be seen in these tables, the UCS value is exceeding the specified USEPA value (340 kPa) at 28 days curing, which means that all the stabilized mixtures tend to increase their UCS with time thereby providing better stability and durability characteristics. It is to be noted that in UK, the 28-days cured soil with UCS value of 700 kPa is accepted and the soil is considered as unhazardous (Alamutu, 2009).

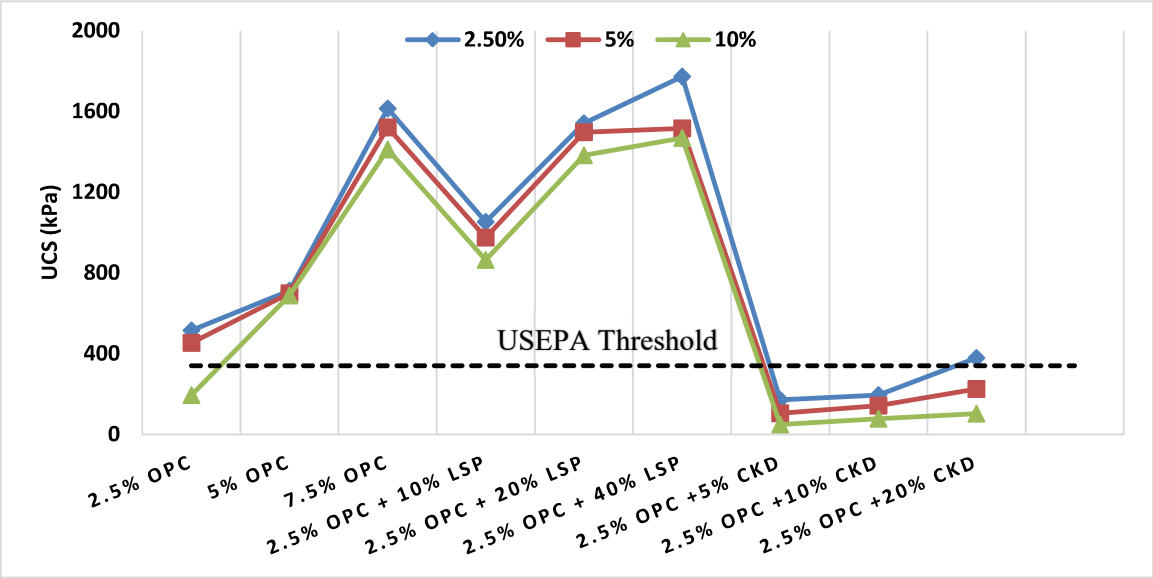


Figure 4.35: Variation of UCS (7-Days-Curing) of Sand with Different Stabilizers at Three Levels of Contamination by Diesel

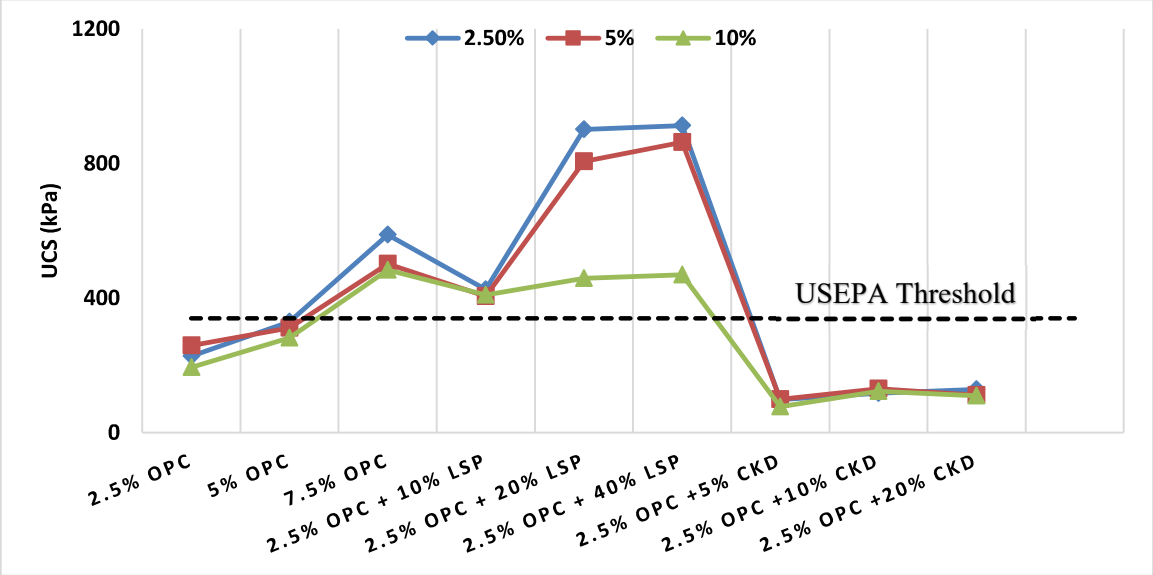


Figure 4.36: Variation of UCS (7-Days-Curing) of Sand with Different Stabilizers at Three Levels of Contamination by Crude Oil

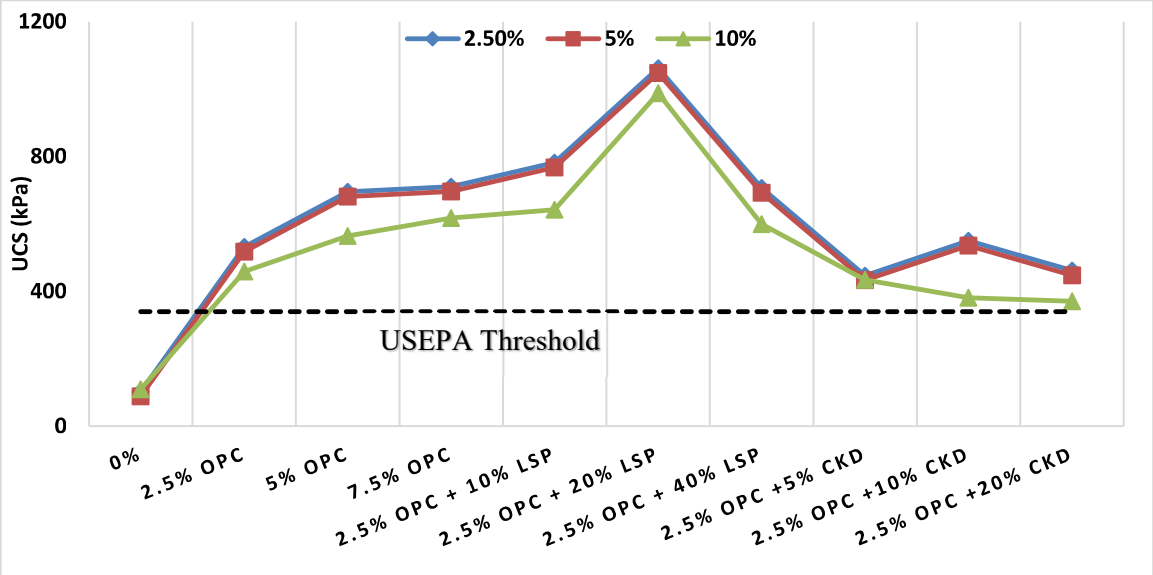


Figure 4.37: Variation of UCS (7-Days-Curing) of Marl with Different Stabilizers at Three Levels of Contamination by Diesel

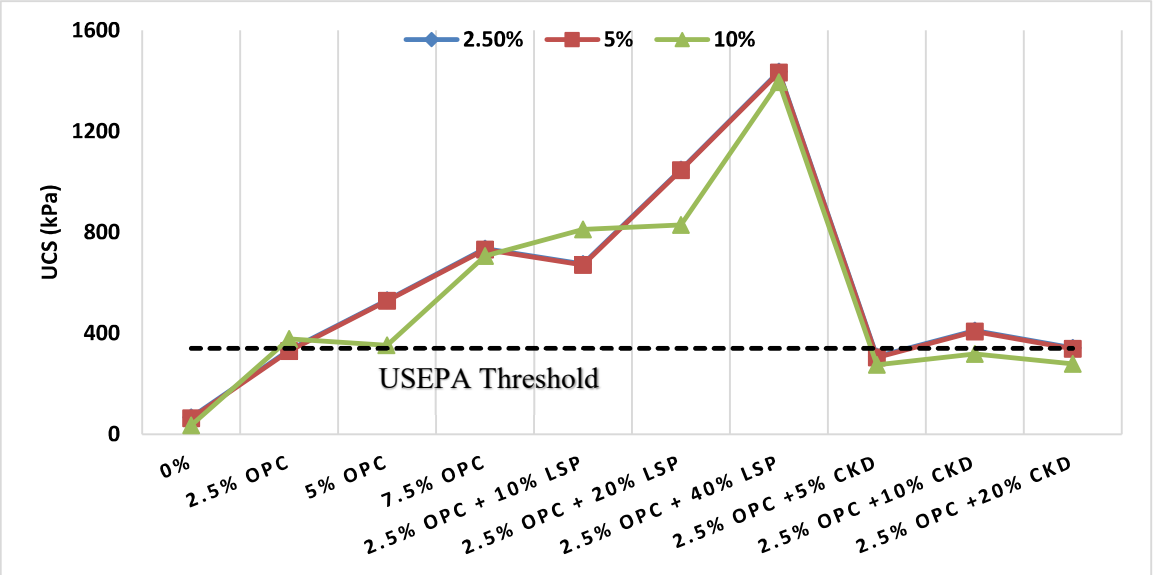


Figure 4.38: Variation of UCS (7-Days-Curing) of Marl with Different Stabilizers at Three Levels of Contamination by Crude Oil

Table 4.8: Summary of UCS Results for 2.5%-Contaminated Sand

Contaminant	Diesel			Crude Oil		
Mixture	**7 Days**	**28 Days**	**90 Days**	**7 Days**	**28 Days**	**90 Days**
2.5% OPC	514.29	605.73	855.35	227.69	450.00	1125.13
5% OPC	711.20	875.89	1389.60	329.28	559.33	1362.57
7.5% OPC	1613.58	1717.11	2001.30	588.11	1136.11	2014.33
2.5% OPC + 10% LSP	1052.90	2196.35	3150.11	425.23	820.22	1608.00
2.5% OPC + 20% LSP	1540.88	3510.05	3902.20	901.26	1226.00	1350.12
2.5% OPC + 40% LSP	1772.28	3600.25	3851.37	913.05	1259.34	1417.03
2.5% OPC + 5% CKD	170.67	305.30	861.00	98.16	480.00	914.32
2.5% OPC + 10% CKD	194.38	321.54	890.08	117.01	501.11	1116.88
2.5% OPC + 20% CKD	378.58	396.56	981.39	128.91	561.00	1205.67

Table 4.9: Summary of UCS Results for 5%-Contaminated Sand

Contaminant	Diesel			Crude Oil		
Mixture	**7 Days**	**28 Days**	**90 Days**	**7 Days**	**28 Days**	**90 Days**
2.5% OPC	453.67	530.09	821.35	258.97	400.25	911.25
5% OPC	698.20	801.28	1202.57	311.48	589.22	1249.35
7.5% OPC	1520.11	1601.30	1650.90	501.33	1019.20	2125.00
2.5% OPC + 10% LSP	975.28	2053.64	2553.05	405.19	780.00	1319.24
2.5% OPC + 20% LSP	1496.09	3211.06	3723.00	806.17	1156.89	1321.05
2.5% OPC + 40% LSP	1515.23	3651.11	3702.00	863.32	1366.00	1400.33
2.5% OPC + 5% CKD	104.99	287.00	801.00	98.89	439.11	850.44
2.5% OPC + 10% CKD	142.36	311.67	822.23	130.73	478.00	916.00
2.5% OPC + 20% CKD	224.54	400.05	887.15	111.36	500.08	1106.58

Table 4.10: Summary of UCS Results for 10%-Contaminated Sand

Contaminant	Diesel			Crude Oil		
Mixture	**7 Days**	**28 Days**	**90 Days**	**7 Days**	**28 Days**	**90 Days**
2.5% OPC	194.05	405.74	839.70	194.05	356.78	741.00
5% OPC	687.99	758.55	1291.31	282.25	420.00	820.66
7.5% OPC	1411.26	1517.11	1891.09	483.36	801.59	1489.25
2.5% OPC + 10% LSP	864.40	2088.67	3087.14	409.27	613.90	1457.13
2.5% OPC + 20% LSP	1383.04	3351.75	4269.07	458.66	652.71	1270.14
2.5% OPC + 40% LSP	1467.71	3457.59	3880.97	469.25	1351.28	1375.98
2.5% OPC + 5% CKD	49.00	201.11	832.65	77.62	310.48	725.00
2.5% OPC + 10% CKD	77.62	275.20	882.04	123.49	409.27	886.97
2.5% OPC + 20% CKD	102.32	331.65	987.88	109.37	335.18	685.25

Table 4.11: Summary of UCS Results for 2.5%-Contaminated Marl

Contaminant	Diesel			Crude Oil		
Mixture	**7 Days**	**28 Days**	**90 Days**	**7 Days**	**28 Days**	**90 Days**
Untreated	**102.32**	**137.6**	**162.3**	**67.04**	**91.73**	**102.32**
2.5% OPC	532.40	1093.74	2189.22	332.89	521.46	1561.03
5% OPC	695.39	1594.74	3004.215	531.52	854.51	2535.145
7.5% OPC	710.20	1820.54	3113.57	735.45	1198.15	3221.73
2.5% OPC + 10% LSP	782.17	1399.89	2492.96	674.43	1218.05	2273.53
2.5% OPC + 20% LSP	1061.93	1923.39	3223.25	1049.25	1778.72	3365.82
2.5% OPC + 40% LSP	706.86	1299.99	1912.61	1436.61	1627.4	3043.78
2.5% OPC + 5% CKD	447	863.885	1380.91	308.11	557	1057.635
2.5% OPC + 10% CKD	550.37	1097.64	1697.72	410.17	763.30	1485.14
2.5% OPC + 20% CKD	461.76	823.76	1426.36	341.50	639	1211.46

Table 4.12: Summary of UCS Results for 5%-Contaminated Marl

Contaminant	Diesel			Crude Oil		
Mixture	**7 Days**	**28 Days**	**90 Days**	**7 Days**	**28 Days**	**90 Days**
Untreated	**88.20**	**148.18**	**239.91**	**63.51**	**84.68**	**119.96**
2.5% OPC	518.28	1104.32	2266.83	329.36	514.41	1578.67
5% OPC	681.28	1605.32	3081.83	527.99	847.46	2552.79
7.5% OPC	696.08	1831.12	3191.18	731.92	1191.10	3239.37
2.5% OPC + 10% LSP	768.05	1410.47	2570.57	670.90	1211.00	2291.17
2.5% OPC + 20% LSP	1047.81	1933.97	3300.86	1045.72	1771.67	3383.46
2.5% OPC + 40% LSP	692.75	1310.57	1990.22	1433.08	1620.35	3061.42
2.5% OPC + 5% CKD	432.88	874.47	1458.52	304.58	549.95	1075.28
2.5% OPC + 10% CKD	536.25	1108.22	1775.33	406.64	756.25	1502.78
2.5% OPC + 20% CKD	447.64	834.34	1503.97	337.97	631.95	1229.10

Table 4.13: Summary of UCS Results for 10%-Contaminated Marl

Contaminant	Diesel			Crude Oil		
Mixture	**7 Days**	**28 Days**	**90 Days**	**7 Days**	**28 Days**	**90 Days**
Untreated	**109.37**	**176.41**	**529.22**	**35.28**	**38.81**	**91.73**
2.5% OPC	458.66	966.72	1958.13	377.51	635.07	1774.66
5% OPC	564.51	1446.54	2910.73	352.82	557.45	2116.89
7.5% OPC	617.43	1686.46	2928.37	705.63	1174.88	3224.74
2.5% OPC + 10% LSP	642.12	1277.19	2723.74	811.48	1400.00	2575.56
2.5% OPC + 20% LSP	987.88	1774.66	2766.08	829.12	1481.83	2960.12
2.5% OPC + 40% LSP	599.79	1164.29	1799.36	1395.00	1570.03	2991.88
2.5% OPC + 5% CKD	433.96	910.26	1407.74	275.20	575.09	1114.90
2.5% OPC + 10% CKD	381.04	822.06	1393.62	317.53	589.20	1263.08
2.5% OPC + 20% CKD	370.46	709.16	1287.78	278.72	560.98	1129.01

4.3.4 Permeability

The coefficient of permeability (k) of the soils contaminated by 10% diesel and crude oil is presented numerically in Table 4.14. The "k" values are compared with the requirement of permeability for the treated soil (10^{-4} to 10^{-8} cm/sec) that is provided by the USEPA (USEPA, 1989). Referring to the data in Table 4.14, the increase in stabilizers content has decreased the permeability for all soils and contaminants. As shown in Table 4.14, in the case of sand contaminated by diesel, the addition of OPC has resulted in a significant reduction in the permeability value (a reduction of 94% in the case of 2.5% OPC, as compared to the untreated sand). Similar behavior is observed in all

other cases. The data in the table also display the variation between the effects of the different stabilizers. For example, in the case of sand contaminated by diesel, a large reduction is observed in the permeability with LSP addition as compared to OPC. This effect is due to the combination of 2.5% OPC and LSP and the effect of particle size which plays a major role in decreasing the permeability (and increasing the UCS, as discussed before). The same behavior was observed in all the other cases with different contaminant and stabilizers.

The data in Table 4.14 indicate that all the treated marly soil (for both diesel and crude oil contamination cases) have passed the permeability requirement. Moreover, the contaminated marl has low permeability (lower than that of the sand) that decreased further with the addition of the stabilizers. This reduction is due to the high presence of fines in the marl as a result of clogging the voids in the soil structure. Increasing the fines content by adding stabilizers tends to enhance the performance of the mixture and resulting in decreasing the permeability.

On the other hand, for the diesel-contaminated sand, five mixes have passed the requirements and these are 7.5% OPC (alone), 20% LSP, 40% LSP, 10% CKD and 20% CKD (with the addition of 2.5% OPC). In the case of the sand contaminated with crude oil, all the LSP mixes have passed the permeability requirements plus the 20% CKD mixture. This behavior is due to the low fines content in the original sand which resulted in a higher permeability. Therefore, those samples that have passed the USEPA criterion (fallen withiin the range 10^{-4} to 10^{-8} cm/sec) can be considered as “unhazardous” and will not affect the surrounding soils if well placed in field.

Table 4.14: Permeability of Sand and Marl Contaminated by 10% Diesel and Crude Oil

	Permeability of Sand ($\times 10^{-4}$ cm/sec)		Permeability of Marl ($\times 10^{-4}$ cm/sec)	
Mixture	**Diesel**	**Crude Oil**	**Diesel**	**Crude Oil**
Untreated	27.90	68.70	2.510	4.080
2.5% OPC	1.653	4.051	**0.128**	**0.456**
5% OPC	1.558	3.569	**0.126**	**0.276**
7.5% OPC	**0.265**	3.499	**0.097**	**0.231**
2.5% OPC + 10% LSP	1.085	**0.805**	**0.026**	**0.107**
2.5% OPC + 20% LSP	**0.152**	**0.239**	**0.012**	**0.031**
2.5% OPC + 40% LSP	**0.128**	**0.073**	**0.006**	**0.012**
2.5% OPC + 5% CKD	1.539	1.879	**0.090**	**0.327**
2.5% OPC + 10% CKD	**0.515**	1.646	**0.067**	**0.276**
2.5% OPC + 20% CKD	**0.469**	**0.336**	**0.046**	**0.049**

4.3.5 TCLP Analysis

As reported in Section 3.5.5, the samples that passed the strength and permeability requirements were considered for TCLP analysis to assess the quantity of heavy metals that are present in the leaching fluid. Both Tables 4.15 and 4.16 present the heavy metals quantities in some heavily contaminated samples of sand and marl. For this analysis, only worst scenario (10% contamination) was considered so that if these samples have passed the USEPA criterion for heavy metals content, then the other scenarios (2.5% and 5% contamination) would definitely pass the criterion.

Major heavy metals were considered in this analysis (Table 2.8). As shown in the data in Tables 4.15 and 4.16, all the samples that were tested have passed the USEPA requirements for heavy metals. In fact, the amounts of heavy metals were minimal and much lower than the detection limits of the ICP device. Therefore, it is safe to consider

the S/S treatment as a success because the heavy metals concentration in the contaminated soil is very low. However, a visible reduction can be observed, like in the case of Ba in contaminated sand. The addition of the LSP has decreased the Ba concentration by nearly 68%. With such low concentrations compared to the USEPA requirements, it is safe to assume that all the contaminated mixes have passed the TCLP heavy metals requirements.

4.3.6 TPH Analysis

The results of TPH analysis are shown numerically in Tables 4.17 and 4.18. It can easily be noted that in the case of diesel contamination, both the sand and marl have experienced a large reduction in TPH values (about 97%) with 7.5% C and 40% LSP in the case of sand. For the marl, a reduction of nearly 98% has been observed with the addition of 7.5% C, 40% LSP and 20% CKD. For crude oil, a reduction of about 93% was noted with the same proportion of stabilizers used in case of diesel contamination. Therefore, it is safe to consider the S/S treatment as a success in terms of environmental conditions. A large removal ratio is expected due to the formation of solid bodies that immobilize the heavy metals and different hydrocarbons (Shah et al, 2002).

Table 4.15: TCLP Results for Sand (ppm)

	Mixture	As	Ba	Cd	Cr	Pb	Se	V
	Uncontaminated	< 0.01	0.301	< 0.01	< 0.01	0.010	0.020	< 0.01
Diesel	**Untreated**	< 0.01	0.883	< 0.01	< 0.01	0.014	< 0.02	< 0.01
	7.5% OPC	< 0.01	0.679	< 0.01	< 0.01	0.011	< 0.02	< 0.01
	2.5% OPC + 40% LSP	< 0.01	0.274	< 0.01	< 0.01	0.012	< 0.02	< 0.01
Crude Oil	**Untreated**	< 0.01	0.839	< 0.01	< 0.01	< 0.01	< 0.02	< 0.01
	2.5% OPC + 20% CKD	< 0.01	0.244	< 0.01	< 0.01	< 0.01	< 0.02	< 0.01
USEPA Requirement		**5**	**100**	**1**	**5**	**5**	**1**	**25**

Table 4.16: TCLP Results for Marl (ppm)

	Mixture	As	Ba	Cd	Cr	Pb	Se	V
	Uncontaminated	< 0.01	0.107	< 0.01	< 0.01	< 0.01	< 0.02	< 0.01
Diesel	**Untreated**	< 0.01	0.158	< 0.01	< 0.01	< 0.01	< 0.02	< 0.01
	7.5% OPC	< 0.01	0.148	< 0.01	0.046	< 0.01	< 0.02	0.059
	2.5% OPC + 40% LSP	< 0.01	0.074	< 0.01	< 0.01	< 0.01	< 0.02	0.013
	2.5% OPC + 20% CKD	< 0.01	0.171	< 0.01	0.023	< 0.01	< 0.02	< 0.01
Crude Oil	**Untreated**	< 0.01	0.120	< 0.01	< 0.01	< 0.01	< 0.02	< 0.01
	7.5% OPC	< 0.01	0.065	< 0.01	0.047	< 0.01	< 0.02	0.043
	2.5% OPC + 40% LSP	< 0.01	0.091	< 0.01	< 0.01	< 0.01	< 0.02	< 0.01
	2.5% OPC + 20% CKD	< 0.01	0.074	< 0.01	0.020	< 0.01	< 0.02	< 0.01
USEPA Requirement		**5**	**100**	**1**	**5**	**5**	**1**	**25**

Table 4.17: TPH Results for Sand (ppm)

Contaminant	Mixture	TPH	% Reduction in TPH
Diesel	Untreated	54,010	-
	7.5% C	1,587	97.1
	2.5% C + 40% LSP	1,467	97.3
Crude Oil	Untreated	23,516	-
	2.5% C + 20% CKD	1,708	92.7

Table 4.18: TPH Results for Marl (ppm)

Contaminant	Mixture	TPH	% Reduction in TPH
Diesel	Untreated	60,924	-
	7.5% C	1,379	97.7
	2.5% C + 40% LSP	837	98.6
	2.5% C + 20% CKD	1,187	98.1
Crude Oil	Untreated	20,906	-
	7.5% C	1,416	93.2
	2.5% C + 40% LSP	1,373	93.4
	2.5% C + 20% CKD	1,267	93.9

4.3.7 PAH Analysis

Tables 4.19 and 4.20 present the PAH analysis in the selected samples for both sand and marl, respectively. Checking the values in Table 4.19, a reduction of nearly 91% in PAH value has been noted in the case of diesel contamination with 7.5% OPC as compared to the contaminated soil, and a reduction 92 was observed in the case of 2.5% OPC + 40% LSP. On the other hand, a reduction by nearly 91% in the PAH values in the case of crude oil contamination with the addition of 2.5% OPC + 20% CKD. As can be seen in

Table 4.19, the addition of LSP has achieved the highest removal ratio and thus it could be considered as the best stabilizer in our current study.

Table 4.20 shows numerically the PAH values in the case of marl. Similar results for those obtained in the case of sand are obtained. In the case of diesel contamination, a removal ratio of 85% has been achieved when mixing the contaminated marl with 7.5% OPC. A higher ratio has been noted with the addition of 2.5% OPC + 40% LSP (94.10%). When adding the 2.5% OPC + 20% CKD, a ratio of 90% is reported. Therefore, these results have shown that using the LSP as a stabilizer (combined with the 2.5% OPC) will give the highest removal ratio as in the case of contaminated sand. In the case of marl contaminated with crude oil, a removal ratio of 66% has been achieved in the case of 7.5% OPC while a ratio of 80% was obtained in the case of 2.5% OPC + 40% LSP. For the case of CKD, a higher removal ratio was obtained (85%).

Comparing both the results of sand and marl to those limits recommended in Table 4.9, all the PAH values are below the limits provided by the Canadian Council of Ministers of the Environment. It should be noted that these values may vary from one country to another and it depends on the usage of lands and the countries regulations.

Table 4.19: PAH Results for Sand (ppm)

	S-CO [(1)]	S-D [(2)]	S-1[(3)]	S-2[(4)]	S-3[(5)]
Naphthalene	8.596	3.122	0.01	0.01	0.02
Methylnaphthalene	36.702	25.267	1.71	0.96	2.16
Acenaphthene	0.842	4.413	0.69	0.57	0.19
Anthracene	0.669	10.803	0.90	1.01	0.49
Benzo (a) anthracene	0.445	0.250	0.10	0.07	0.04
Chrysene	1.475	1.130	0.79	0.72	1.33
Benzo (b) fluoranthene	1.884	0.010	0.01	0.02	0.06
Benzo (k) fluoranthene	0.039	0.022	0.05	0.03	0.15
Benzo (a) pyrene	0.770	0.012	0.01	0.01	0.04
Total PAH	51.422	45.029	4.27	3.4	4.48
Improvement (%)	-	-	90.52	92.45	91.29

[(1)] S-CO: Sand + 10% Crude Oil; [(2)] S-D: Sand + 10% Diesel; [(3)] S-1: 7.5% C (Diesel); [(4)] S-2: 2.5% C + 40% LSP (Diesel); [(5)] S-3: 2.5% C + 20% CKD (Crude Oil)

Table 4.20: PAH Results for Marl (ppm)

	M-CO [1]	M-D [2]	M-1[3]	M-2[4]	M-3[5]	M-4[6]	M-5[7]	M-6[8]
Naphthalene	0.926	3.646	0.01	0.01	0.01	0.03	0.01	0.01
Methylnaphthalene	13.352	22.254	2.94	0.80	1.88	3.92	3.06	1.61
Acenaphthene	1.792	3.647	1.00	0.46	0.62	0.34	0.34	0.19
Anthracene	0.576	8.903	0.88	0.88	0.80	0.80	0.05	0.62
Benzo(a) anthracene	0.433	0.460	0.16	0.22	0.12	0.17	0.14	0.04
Chrysene	1.514	1.418	1.11	0.05	0.77	1.90	0.57	0.43
Benzo (b) fluoranthene	2.289	2.182	0.02	0.01	0.02	0.05	0.05	0.04
Benzo (k) fluoranthene	0.256	0.154	0.07	0.08	0.06	0.28	0.18	0.24
Benzo (a) pyrene	0.913	0.051	0.03	0.01	0.04	0.05	0.03	0.14
Total PAH	22.051	42.715	6.22	2.52	4.32	7.54	4.43	3.32
Improvement (%)	-	-	85.44	94.10	89.96	65.81	79.91	84.94

[1] M-CO: Marl + 10% Crude Oil [2] M-D: Marl + 10% Diesel [3] M-1: 7.5% C (Diesel) [4] M-2: 2.5% C + 40% LSP (Diesel) [5] M-3: 2.5% C + 20% CKD (Diesel) [6] M-1: 7.5% C (Crude Oil) [7] M-2: 2.5% C + 40% LSP (Crude Oil) [8] M-3: 2.5% C + 20% CKD (Crude Oil)

4.3.8 SEM and XRD Analysis

Some selected samples were analyzed to assess the changes in fabric and micro-structure of both sand and marl under 10% contamination (worst scenario). Figure 4.39 presents the SEM micrograph for stabilized sand (2.5% OPC + 40% LSP), whereby it could be seen that the sand particles are covered with the calcite ($CaCO_3$) that is coming from the LSP. The calcite is known for its crystalline structure that gives higher strength and thus it is expected to increase the UCS value with the presence of LSP (Mitchell and Soga 2005). Table 4.21 presents the EDS analysis at Location-1 (in Figure 4.39) where it can be seen that the amount of silica is high and there is no trace of calcium element. On the other hand, Table 4.22 shows the EDS analysis at Location-2 where the calcite minerals

are visible in the SEM images and that is why a high amount of calcium is observed compared to the silica. The EDS results show that the calcite minerals are scattered all over the sand particles thereby increasing the roughness of the surfaces and thus increasing the internal friction, resulting in an increase in the UCS of the soil. Table 4.23 shows the XRD semi-quantitative analysis of the same specimen where 53% of calcite and 47% silica are observed.

Figure 4.40 depicts the effect of 20% LSP plus 2.5% OPC on the micro-structure of 10%-crude oil contaminated sand. A variation in the particles size is observed (Figure 4.40(a)) while Figure 4.40 (b) shows the formation of extra sheets of calcite and the presence of coating that was evidenced by the EDS results in Table 4.24. EDS analysis shows an increase in the carbon content as observed in the contaminated soil (Section 4.2.8). Such results show that the presence of high amounts of hydrocarbons have affected the strength of the sand (458.66 kPa) as compared to other mixtures. Table 4.25 shows the XRD analysis of the same specimen.

The SEM micrograph in Figure 4.41 displays the calcite minerals attached to the surfaces of the marl particles. Table 4.26 shows the EDS analysis of the 10%-crude oil contaminated marl with 2.5% OPC + 40% LSP. A high amount of carbon could be observed which may be due to the presence of hydrocarbons that did not affect the strength that much, where a value of 1395 kPa was achieved due to the increase in surface roughness and particles interlocking. Although the calcite ratio is relatively small compared to that in Figure 4.39 (17.2% compared to 53%), a high UCS value was attained (1395 kPa). This is due to the conjoint presence of dolomite in the marl (66.2%) that has crystalline structure thereby increasing the strength.

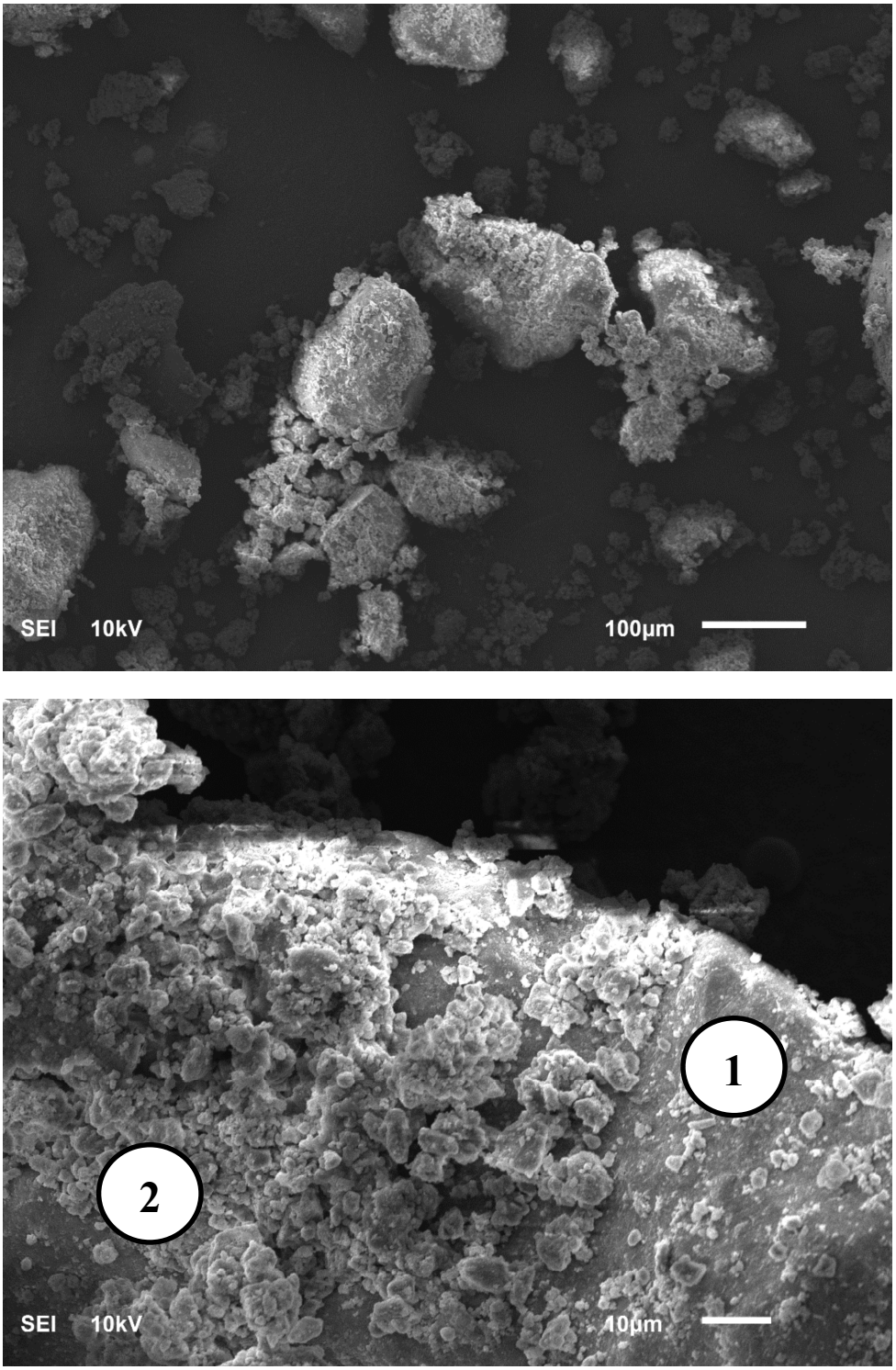


Figure 4.39: SEM Image of 10%-Diesels Stabilized Sand (2.5% OPC + 40% LSP) at a magnification of: (a) 100 µm (b) 10 µm

Table 4.21: EDS Analysis of 10-Diesel Stabilized Sand (2.5% OPC + 40% LSP) (Location-1)

Element	Weight (%)
C	26.49
O	45.70
Mg	1.07
Al	0.88
Si	25.86
Total:	100.00

Table 4.22: EDS Analysis of 10-Diesel Stabilized Sand (2.5% OPC + 40% LSP) (Location-2)

Element	Weight (%)
C	27.49
O	44.62
Si	2.17
Ca	25.72
Total:	100.00

Table 4.23: XRD Analysis of 10-Diesel Stabilized Sand (2.5% OPC + 40% LSP)

Mineral	Formula	Weight (%)
Quartz	SiO_2	47
Calcite	$CaCO_3$	53

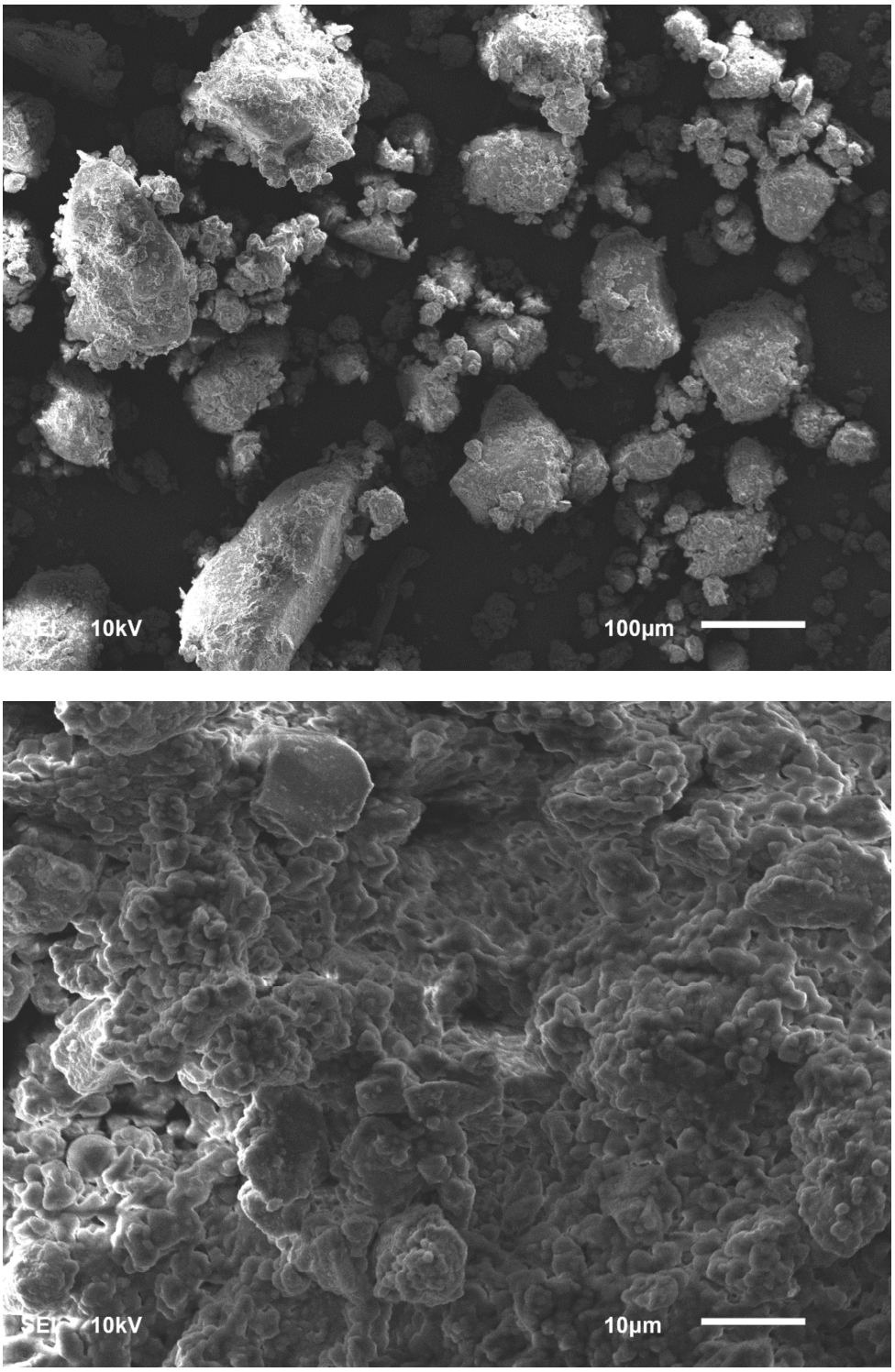


Figure 4.40: SEM Image of 10%-Crude Oil Stabilized Sand (2.5% OPC + 20% LSP) at a magnification of: (a) 100 µm (b) 10 µm

Table 4.24: EDS Analysis of 10%-Crude Oil Stabilized Sand (2.5% OPC + 20% LSP)

Element	Weight (%)
C	59.07
O	22.92
Si	5.10
Ca	12.91
Total:	100.00

Table 4.25: XRD Analysis of 10%-Crude Oil Stabilized Sand (2.5% OPC + 20% LSP)

Mineral	Formula	Weight (%)
Quartz	SiO_2	67.4
Calcite	$CaCO_3$	29.65
Rankinite	$Ca_3Si_2O_7$	3.6

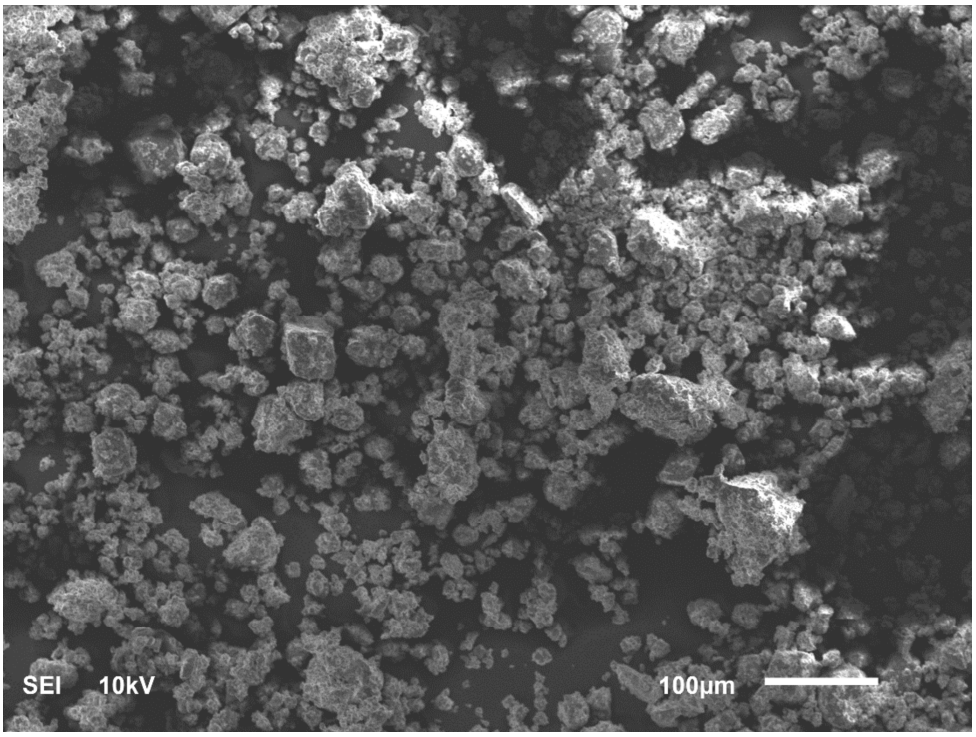


Figure 4.41: SEM Image of 10%-Crude Oil Stabilized Marl (2.5% OPC + 40% LSP) at a magnification of: (a) 100 µm (b) 10 µm)

Table 4.26: EDS Analysis of 10%-Crude Oil Stabilized Marl (2.5% OPC + 40% LSP)

Element	Weight (%)
C	52.27
O	29.37
Mg	1.95
Si	4.48
Ca	11.93
Total:	100.00

Table 4.27: XRD Analysis of 10%-Crude Oil Stabilized Marl (2.5% OPC + 40% LSP)

Mineral	Formula	Weight (%)
Dolomite	$CaMg(CO_3)_2$	66.2
Quartz	SiO_2	16.5
Calcite	$CaCO_3$	17.2

CHAPTER 5

UTILIZATION OF STABILIZED-CONTAMINATED SOILS

After evaluating the properties of the stabilized-contaminated marl and sand soils and verifying whether they are considered as “unhazardous” materials based on the USEPA requirements, as discussed before, the stabilized soils were considered for utilization in pavement applications. As was shown in Table 2.4, a minimum 7-day UCS of 1380 kPa is required in order to consider whether the soils are suitable as pavement materials.

5.1 Unconfined Compressive Strength

In this section, the results obtained for UCS (Section 4.3.3) is compared with the ACI minimum 7-day UCS of 1380 kPa for use as sub-base material for pavement, as specified by the ACI (Table 2.6). It can be observed from Figures 5.1 to 5.12 that some of the stabilized soil mixtures have passed the ACI requirement. As can be seen in Figure 5.1 and 5.2, only the contaminated sand treated with 7.5% OPC in the case of diesel contamination has passed the ACI threshold value. On the other hand, the soil mixtures treated using cement and LSP have attained better results for sand contaminated with diesel, as shown in Figure 5.3, while no samples have passed the requirement in the case of crude oil contamination, as shown in Figure 5.4. The behavior of sand treated with CKD is shown graphically in Figures 5.5 and 5.6. None of the samples that were treated with CKD passed the requirements of ACI due to the poor performance of CKD in the presence of petroleum hydrocarbons, as was discussed in Section 4.3.3.

In the case of contaminated marl, as shown in Figures 5.7 to 5.12, only one mixture has reached the threshold value, and that is the marl stabilized by 2.5% OPC + 40% LSP, as shown in Figure 5.10 in the case of crude oil contamination. Tables 5.1 and 5.2 present a summary of the samples passing ACI criterion and their UCS values.

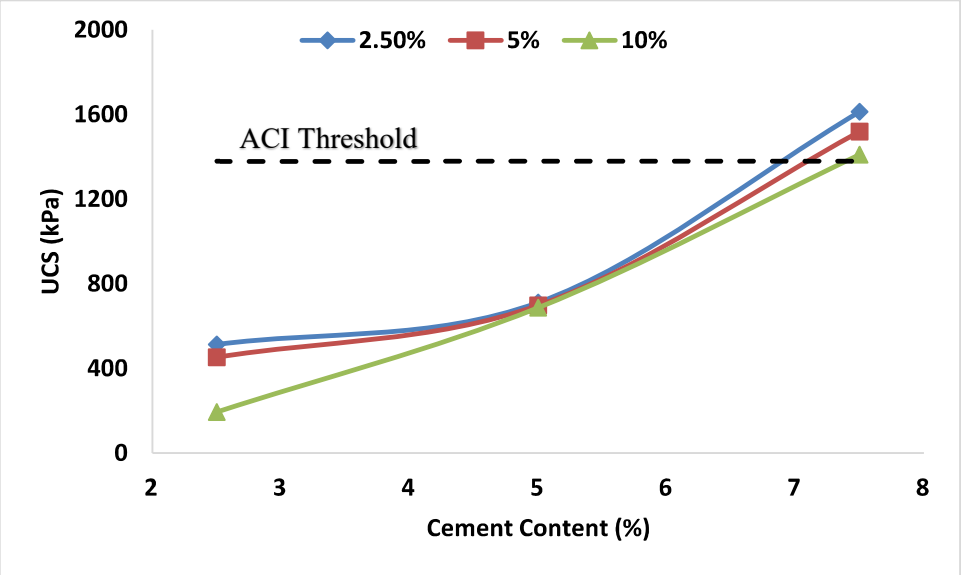


Figure 5.1: UCS Variation with Cement Content for Sand (Different Diesel Contamination Levels)

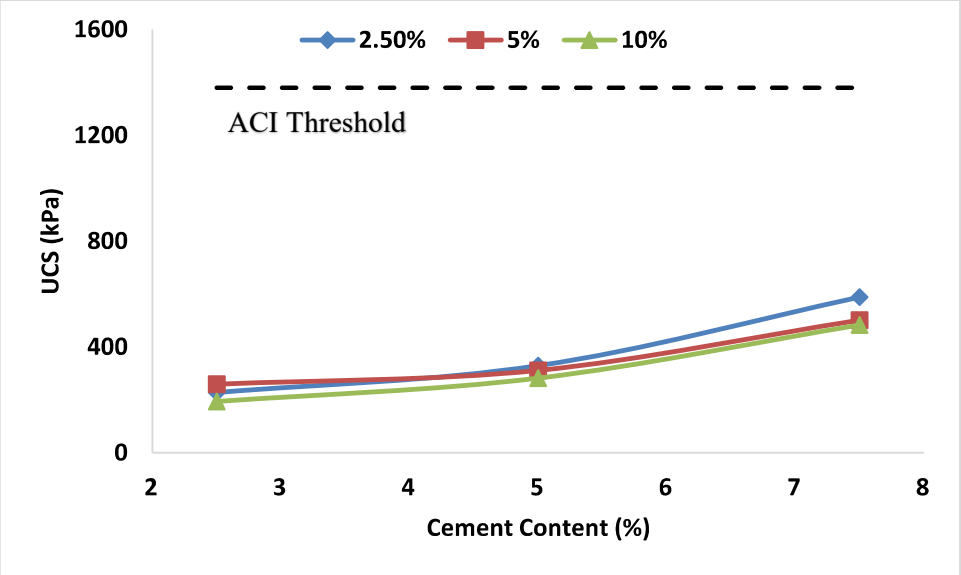


Figure 5.2: UCS Variation with Cement Content for Sand (Different Crude Oil Contamination Levels)

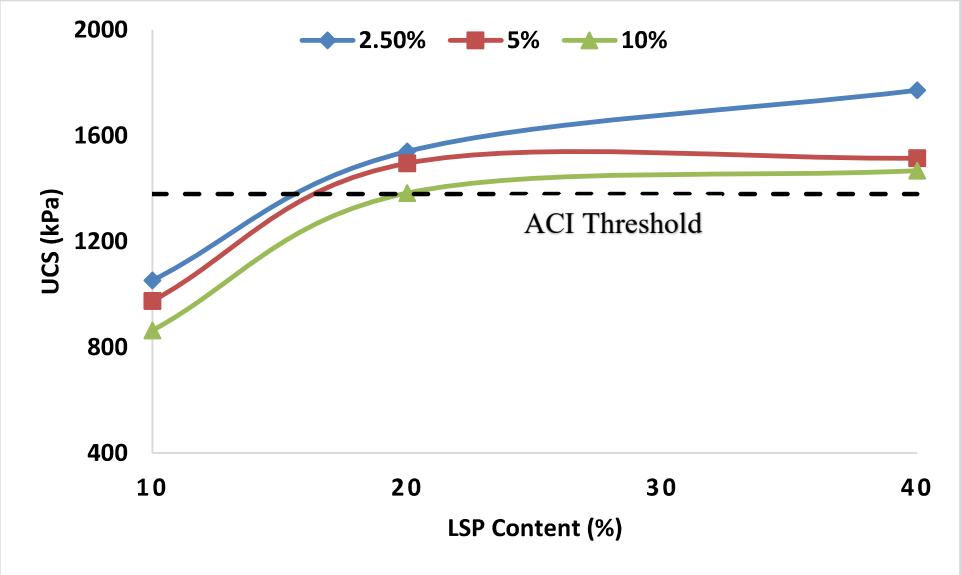


Figure 5.3: UCS Variation with LSP Content for Sand (Different Diesel Contamination Levels)

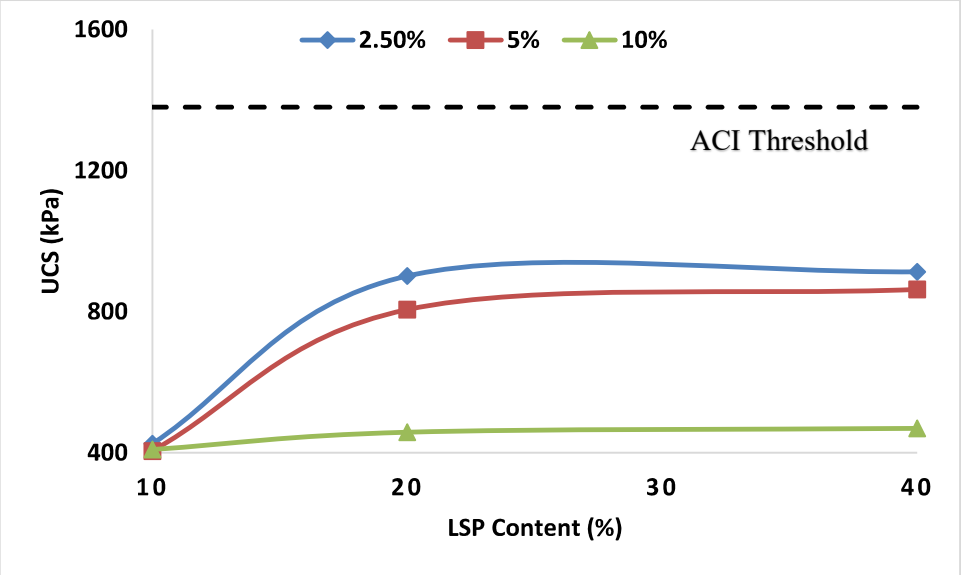


Figure 5.4: UCS Variation with LSP Content for Sand (Different Crude Oil Contamination Levels)

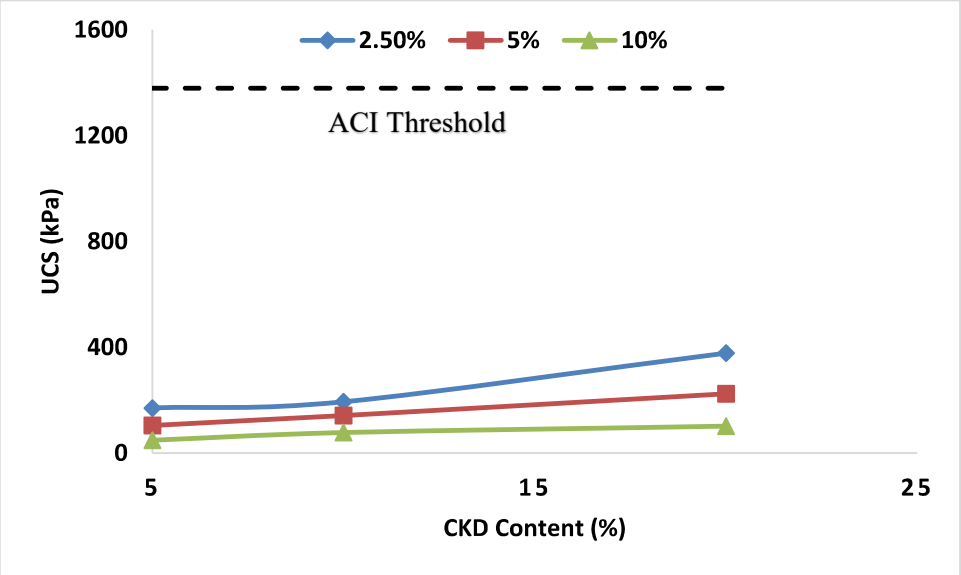


Figure 5.5: UCS Variation with CKD Content for Sand (Different Diesel Contamination Levels)

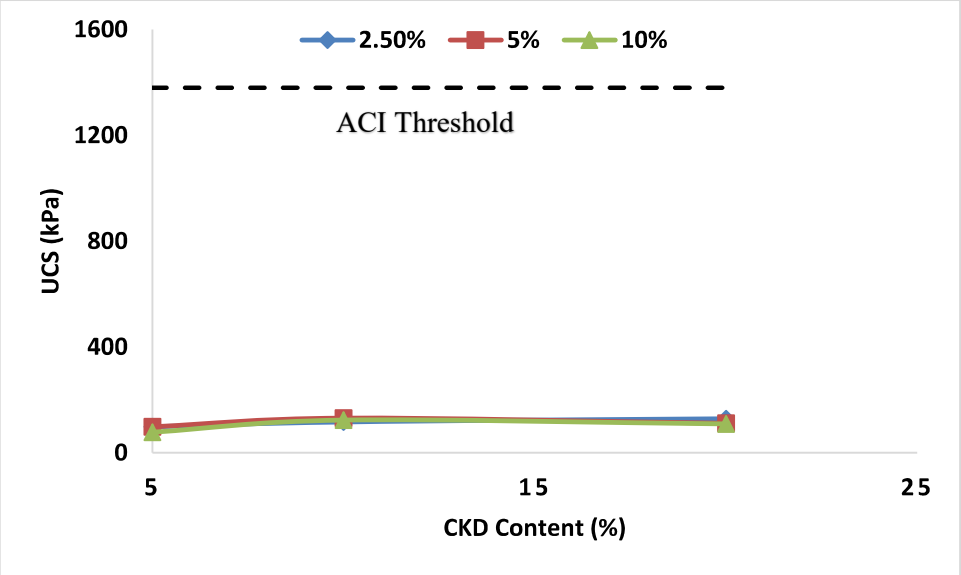


Figure 5.6: UCS Variation with CKD Content for Sand (Different Crude Oil Contamination Levels)

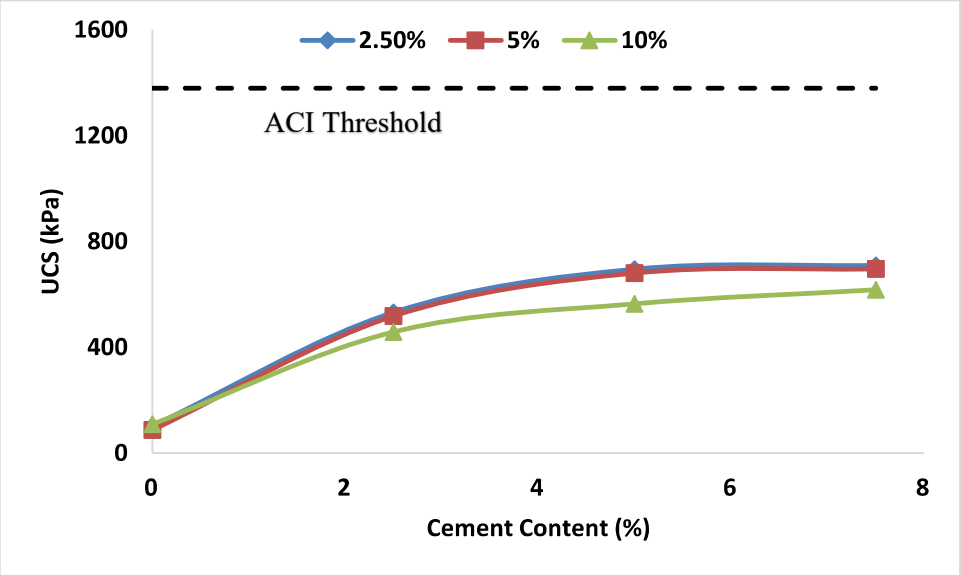


Figure 5.7: UCS Variation with Cement Content for Marl (Different Diesel Contamination Levels)

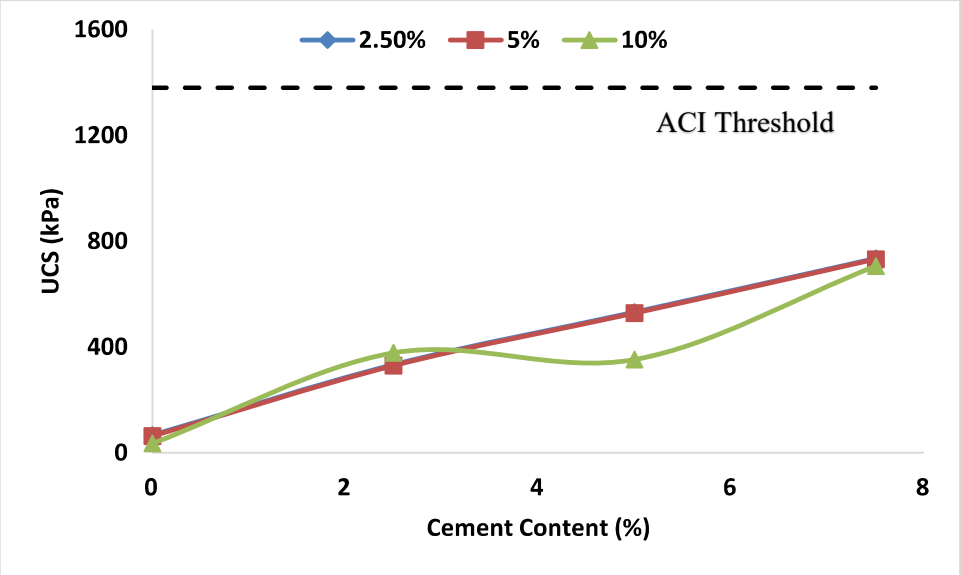


Figure 5.8: UCS Variation with Cement Content for Marl (Different Crude Oil Contamination Levels)

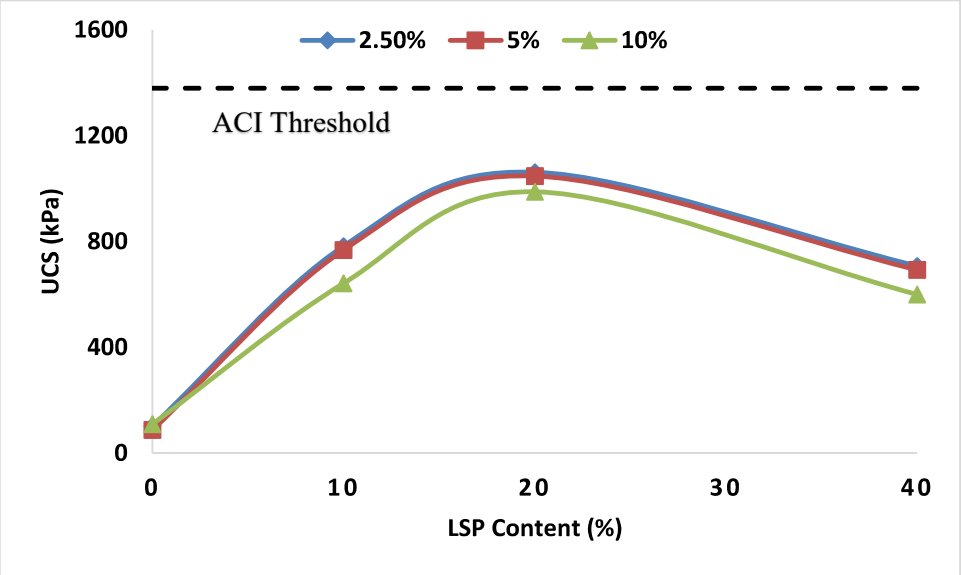


Figure 5.9: UCS Variation with LSP Content for Marl (Different Diesel Contamination Levels)

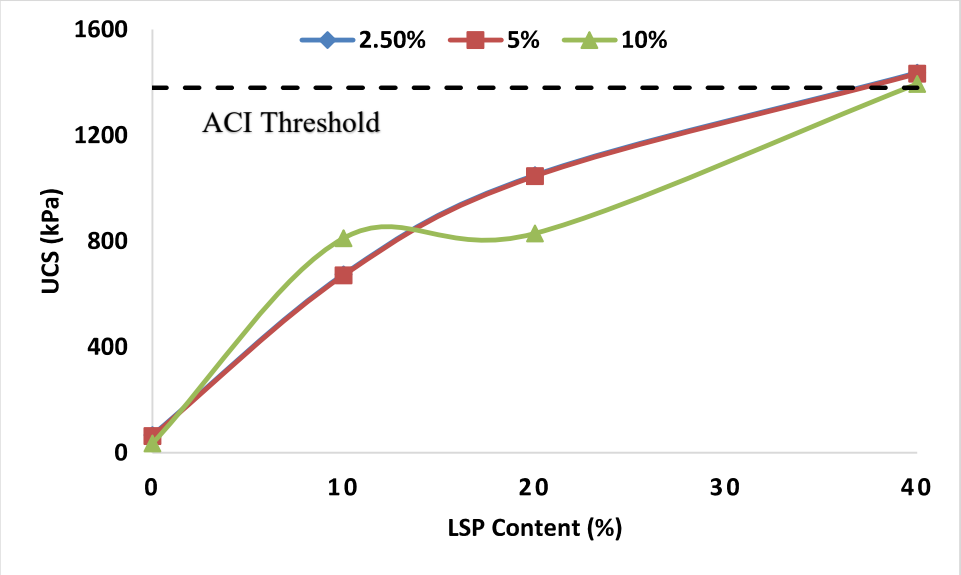


Figure 5.10: UCS Variation with LSP Content for Marl (Different Crude Oil Contamination Levels)

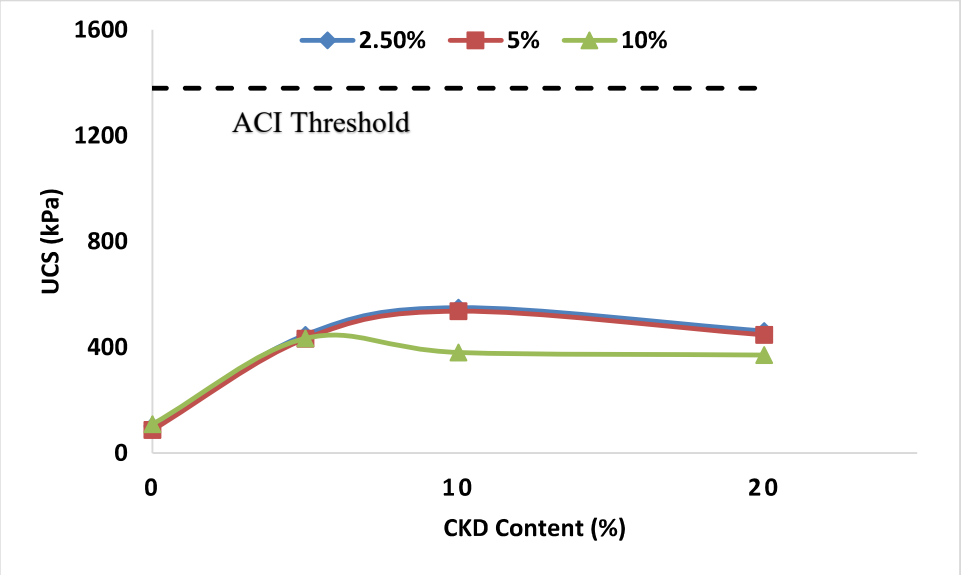


Figure 5.11: UCS Variation with CKD Content for Marl (Different Diesel Contamination Levels)

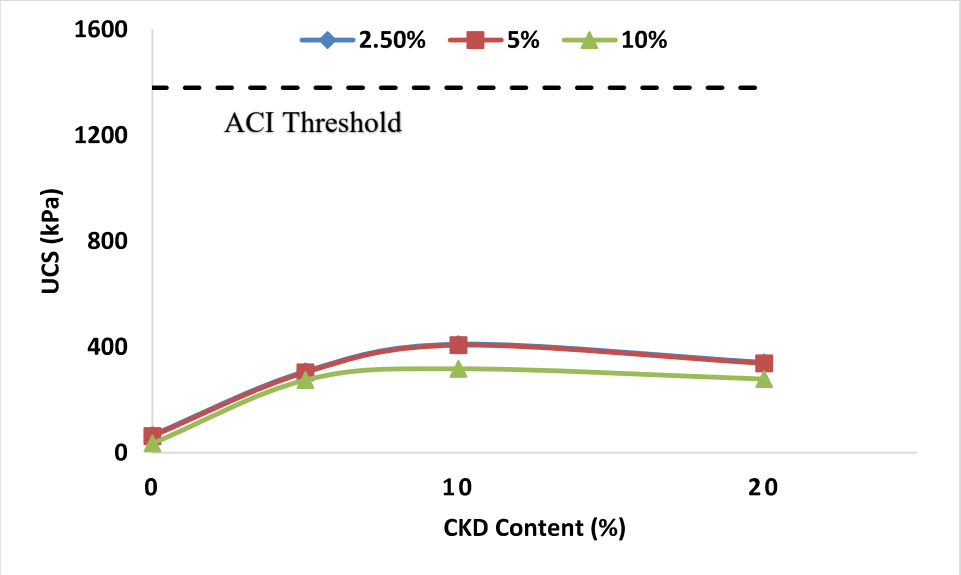


Figure 5.12: UCS Variation with CKD Content for Marl (Different Crude Oil Contamination Levels)

Table 5.1: UCS Values for the Stabilized Contaminated Sand Passing ACI Criterion

	Cont. Level (%)	Mixture	UCS (kPa)	Requirement (kPa)	Application
Diesel	**2.5**	2.5% C + 20% LSP	1540.88	1380	Sub-Base Layer
		2.5% C + 40% LSP	1772.28		
	5	2.5% C + 20% LSP	1496.09		
		2.5% C + 40% LSP	1515.23		
	10	2.5% C + 20% LSP	1383.04		
		2.5% C + 40% LSP	1467.71		

Table 5.2: UCS Values for the Stabilized Contaminated Sand Passing ACI Criterion

	Cont. Level (%)	Mixture	UCS (kPa)	Requirement (kPa)	Application
Crude Oil	2.5	2.5% C + 40% LSP	1436.61	1380	Sub-Base Layer
	5		1433.08		
	10		1395.0		

5.2 California Bearing Ratio (CBR)

As was discussed in Section 3.5.4, the samples that passed the ACI requirements were tested for their CBR values. According to the Asphalt Institute (1970), a CBR value of 20 to 50% is required for using the soil mixture as a sub-base layer. Tables 5.3 and 5.4 depict numerically the soaked CBR values obtained for the selected samples. As shown in these two tables, all the selected samples are approved to be used for sub-base layer materials since their CBR is falling in the range 20-50.

Table 5.3: CBR Values for the Stabilized Contaminated Sand

	Cont. Level (%)	Mixture	CBR (%)	Requirement (%)	Application
Diesel	**2.5**	2.5% C + 20% LSP	39.47	20-50	Sub-Base Layer
		2.5% C + 40% LSP	35.16		
	5	2.5% C + 20% LSP	43.28		
		2.5% C + 40% LSP	40.11		
	10	2.5% C + 20% LSP	46.37		
		2.5% C + 40% LSP	48.83		

Table 5.4: CBR Values for the Stabilized Contaminated Marl

	Cont. Level (%)	Mixture	CBR (%)	Requirement (%)	Application
Crude Oil	2.5	2.5% C + 40% LSP	36.88	20-50	Sub-Base Layer
	5		39.51		
	10		47.24		

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

This research aimed at studying the effects of two types of contaminants (namely, diesel and crude oil) on the geotechnical, environmental and micro-structural properties of two different types of soils that are locally available in eastern Saudi Arabia (sand and marl). The contaminated soils were treated using three types of stabilizers (OPC, LSP and CKD) to enhance the properties of the contaminated soils. Based on the analysis of the results obtained through the experimental program conducted under the present work, the following conclusions were drawn:

- The increase in contamination level on both soils have negatively affected their geotechnical properties by increasing the Atterberg limits, reducing the specific gravity and changing the gradation by forming large clods for both sand and marl. A marginal reduction in the maximum dry density of sand was observed, unlike the marl. The optimum moisture content was reduced with the increase in the contamination level for marl, except for the diesel contamination beyond 2.5% contamination level.
- While there was negative effect of crude oil contamination on UCS of marl, the UCS of marl contaminated with diesel was not affected adversely.
- The S/S treatment of contaminated soils using different combinations of the stabilizers improved the compaction characteristics, unconfined compressive strength, permeability, TCLP, etc., thereby satisfying the USEPA environmental requirements.

- The combination of cement and LSP, used as stabilizer, performed well. However, the performance of the stabilizer obtained by combining cement and CKD was found to be unsatisfactory.
- TCLP results for both sand and marl (contaminated and stabilized) have indicated that all soil samples passed the USEPA criteria for heavy metals content and thus the soils are considered safe in term of heavy metals leachate.
- The results TPH showed a significant removal of hydrocarbons by the stabilizers (more than 90%) for both sand and marl soils. Similarly, the results of PAH analysis have indicated a large removal ratio in the case of sand (more than 90% removal) while marginally lower ratios were obtained in the case of marl.
- SEM, EDS and XRD results of the contaminated soils have shown the formation of coating of hydrocarbons on the surfaces of these soils' particles which affected the geotechnical properties. In the case of stabilized soils, the SEM, EDS and XRD analyses have shown the formation of calcite on the surface of soil particles with the addition of LSP combined with 2.5% OPC.
- Some S/S-treated mixtures that passed both the ACI criterion for minimum UCS and CBR can be utilized as sub-base materials in pavement construction. Those are 2.5% OPC + 20% LPS & 2.5% OPC + 40% LSP for diesel contaminated sand and 2.5% OPC + 40% LSP for marl contaminated by crude oil.

At the conclusions of this research program, **the following recommendations are presented in order to extend the research to another scale:**

- Repeat the same experimental program for different types of contaminants, either hydrocarbons, like benzene and kerosene, or other chemicals such as sulphuric and phosphoric acids;
- Use different types of stabilizers, such as fly ash and electric arc furnace dust (EAFD), which are available in the Eastern province), have to be investigated.
- Study the effect of contamination on the structure of the soil using the SEM without drying the samples in order to assess the changes in the structure with the presence of the oil.
- Study the effect of temperature on the geotechnical properties of the contaminated and treated soils, particularly in the hot exposure conditions of the Arabian Gulf.

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